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Examining Foot and Lower Leg Muscular Activation During Slip Recovery

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By

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Abstract

Slips during gait are the leading cause of falls and subsequent serious injury in young and older adults. Reactive balance responses generated by the lower limb muscles can restore balance and minimize the chance of experiencing a fall. The purpose of this study was to examine the role of the deep muscles in the lower leg and muscles within the foot during recovery from an unexpected slip perturbation. We hypothesized that lower leg musculature and intrinsic foot muscles would exhibit an earlier onset, longer duration, and increased magnitude during slips compared to level walking and that muscle activity would have a reduced magnitude within individuals with Hallux Valgus.

Young adults with unaffected feet (n= 16, age: 24 ± 1.55) and those with Hallux Valgus (n= 4, age: 24.75 ± 1.71) completed a series of level walking trials with unexpected slip perturbations elicited with waxed paper adhered to the underside of a sandpaper mat. Participants were equipped with 12 IRED markers to collect kinematics of body segments and were recorded using an OptoTrak Certus camera system. Kinematics were used to calculate whole body centre of mass (COM) velocity, ankle displacement/velocity, and foot angle range/angular velocity in the perturbed/leading limb. Muscle activity was collected from a total of 10 lower limb and foot muscles using a combination of surface and fine-wire intramuscular electromyography (EMG). Force plates were used to record ground reaction forces and identify gait cycle timing during level walking and unexpected slip trials.

Overall, 20 participants experienced at least one slip with the most common type of slip occurring at toe off (93% of all slips that occurred were at toe off). Muscle activation onset, duration, and normalized magnitude across slips (slip 1, 2, and 3) was highly variable. In general, extrinsic and intrinsic foot muscles exhibited a delayed onset, longer duration of muscle activity,

and an increase in normalized magnitude in response to slip perturbations compared to level walking. This was observed in both unaffected feet and those with Hallux Valgus. Ankle marker velocity in the anterior-posterior direction revealed the foot travelled backwards when experiencing toe off slips. Ankle angular velocity range increased indicating that the rate in which the ankle moved through plantarflexion and dorsiflexion was faster during slips. Average COM velocity in the anterior-posterior direction increased during slips. Propulsive (anterior-posterior shear) force during the second half of the contact (stance) phase was reduced as a result of a toe off slip perturbation. Additionally, loading rate in the anterior-posterior direction decreased whereas vertical unloading rate increased prior to toe off. Ground reaction forces were not significantly different in the Hallux Valgus sub-group.

These findings suggest that lower leg and foot musculature assist in balance recovery from a toe off slip, ensuring a continuous gait trajectory is maintained. Additionally, observations within muscle activation patterns during gait and slips in individuals with Hallux Valgus provided rationale to further examine the muscle timing and magnitude of the lower leg and foot muscles. Future work may provide further evidence that structural changes in the foot due to Hallux Valgus influences muscle mechanics and thus, dynamic balance.

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Table of Contents

List of Figures

Glossary of Terms

Abduction: Sideways movement of the body segment away from the midline or sagittal plane (Hamill et al. 2015)

Abductor hallucis (AbdH): A muscle that originates at the medial calcaneus and inserts on the medial base of the proximal phalanx of the first toe. It is the primary muscle responsible for abduction of the first toe (Hamill et al. 2015; Moore et al. 2015)

Adduction: Sideways movement of the body segment toward the midline or sagittal plane (Hamill et al. 2015)

Adductor hallucis (AddT): A muscle that consists of an oblique and transverse head. The oblique head originates at the second, third, and fourth metatarsal where the transverse head originates on the plantar ligaments of the third, fourth, and fifth metatarsophalangeal joints. Both tendons insert on the lateral side of the proximal phalanx of the first toe. It is the primary muscle responsible for adduction of the first toe and assists in maintaining the transverse arch of the foot (Hamill et al. 2015; Moore et al. 2015)

Anterior posterior (AP): Movement along the y-axis in the transverse plane with anterior representing the front of the body and posterior representing the back of the body (Hamill et al. 2015)

Base of support (BOS): The amount of surface in contact with the environment that provides stability, typically involving the area under the feet bordered by the anterior, posterior, medial, and lateral aspects of the foot/feet in contact with the ground (McIlroy and Maki 1993)

Body Weight (BW): Standard unit of an individual's mass (kg) that can be used to normalize ground reaction forces (kg*acceleration due to gravity; 9.81m/s^2) (Hall 2012)

Centre of mass (COM): Net location of the balancing point of the body within three-dimensional space and the individual's mass is evenly distributed, sum of the moments is equal to zero (Winter 2009; Hamill et al. 2015)

Dorsiflexion: Rotation of the foot segment about the ankle up in the sagittal plane; movement toward the lower leg segment (Hamill et al. 2015)

Electromyography (EMG): An experimental technique concerned with the development, measurement/recording, and analysis of myoelectric signals during voluntary neuromuscular activation of muscles during postural tasks and functional movements. Myoelectric signals are formed by physiological variations in the state of the muscle fiber membranes (Konrad 2006; Hamill et al. 2015).

Eversion: Movement in which the lateral boarder of the foot segment lifts so the plantar surface of the foot faces away from the midline of the body (Hamill et al. 2015)

Extension: Movement of a segment away from an adjacent segment so that the angle between the two segments is increased (Hamill et al. 2015)

Extensor hallucis brevis (EHB): A muscle that originates on the dorsal aspect of the calcaneus and inserts on the dorsal aspect of the base of the proximal phalanx of the first toe. Primary muscle responsible for extension of the first toe (Garrow et al. 2001; Moore et al. 2015)

Extrinsic foot muscles: Muscles within the lower limb that have origins in the lower leg and long tendons that cross the ankle and metatarsophalangeal joints assisting with movement at both the ankle and metatarsophalangeal joints (Zelik et al. 2015)

Flexion: Movement of a segment toward an adjacent segment so that the angle between the two is decreased (Hamill et al. 2015)

Flexor hallucis longus (FHL): A muscle that is originates on the inferior two thirds of the posterior aspect of the fibula and interosseous membrane and inserts on the base of the distal phalanx of the first toe. Primary muscle responsible for flexion of the first toe and adduction of the forefoot and assists with ankle plantar flexion and inversion (Hamill et al. 2015; Moore et al. 2015)

Ground reaction force (GRF): Reactive forces of the ground acting on the body, that are equal in magnitude and opposite in direction to the forces applied to the ground by the individual (Newton's 3rd Law). Measured using a force plate in the vertical, anterior-posterior, medial-lateral components, reported in Newtons (N) (Hall 2012)

Hallux Valgus (HV): Foot deformity caused by degenerative joint disease; it is characterized by the lateral deviation of the first toe (Hall 2012; Moore et al. 2015)

Intrinsic foot muscles: Muscles within the foot that have both their origins and insertions within the foot and provide structural support for the foot (Kelly et al. 2012; Zelik et al. 2015)

Inversion: Movement in which the medial boarder of the foot segment lifts so the plantar surface of the foot faces toward the midline of the body (Hamill et al. 2015)

Kinematics: Examines the spatial and temporal components of motion without referring to the forces that cause the motion (i.e., position, velocity, and acceleration) (Hamill et al. 2015)

Kinetics: Examines the forces that contribute to motion acting on the body such as gravity and ground reaction forces (Hamill et al. 2015)

Medial longitudinal arch: Located on the medial aspect of the plantar surface of the foot and is supported by the tibialis anterior, tibialis posterior, and peroneus longus tendons, assisting with distribution of weight over the foot (Hall 2012; Moore et al. 2015)

Metatarsophalangeal (MTP): Condyloid synovial joint where the heads of the metatarsal bones articulate with the bases of the proximal phalanges. It can perform movements such as flexion, extension, limited abduction, adduction, and circumduction (Moore et al. 2015)

Peroneus longus (PL): A muscle that originates on the head and superior two thirds of the lateral surface of the fibula and inserts on the base of the first metatarsal and medial cuneiform. It is the primary muscle responsible for eversion at the ankle and abduction of the forefoot and also assists with ankle plantarflexion (Hamill et al. 2015; Moore et al. 2015)

Plantarflexion: Movement of the foot segment downward in the sagittal plane; movement away from the lower leg segment (Hamill et al. 2015)

Required coefficient of friction (RCOF): The required dynamic coefficient of friction that must be available at the shoe-floor interface to prevent slipping at heel contact or toe off (Lockhart 2013)

Tibialis anterior (TA): A muscle that originates from the upper lateral tibia and interosseous membrane and inserts onto the medial plantar surface of the first cuneiform and base of the first metatarsal. It is the primary muscle responsible for ankle dorsiflexion and inversion (Hamill et al. 2015; Moore et al. 2015)

Tibialis posterior (TP): A muscle that originates from the interosseous membrane, posterior surface of the tibia and fibula and inserts on the inferior aspect of the navicular and bases of second to fourth metatarsals. It is primarily responsible for inversion at the ankle and assists with ankle plantarflexion (Hamill et al. 2015; Moore et al. 2015)

Transverse arch: Located within the forefoot region on of the foot, it is supported by the medial longitudinal arch and the tendons of peroneus longus and tibialis posterior to assist with distribution of weight over the foot (Moore et al. 2015)

1.0 Introduction

Falls are the leading cause of serious injury in Canada for both young and older adults. Environmental hazards such as snow and ice account for a significant number of falls, however, it has been previously reported that the leading cause of falls resulting in injury occurred on a non-icy surface involving unexpected perturbations, such as a slip during gait (Redfern et al. 2001; Wilkins and Park 2004). Falls are often a result of an inadequate recovery of balance following unexpected perturbations such as a slip or trip (Redfern et al. 2001; Marigold et al. 2003). Slips have been identified as a major factor contributing to falls due to the truly unexpected characteristics (Redfern et al. 2001; Moyer et al. 2006).

The feet serve as an important interface between the environment and the body. Human factors such as gait and the integrity of the neuromuscular system are crucial in regaining balance control when reacting to a slip (Redfern et al. 2001). A slip is detected at initial contact via plantar pressure and ankle joint position (Lockhart et al. 2005). Once a slip is detected, corrective joint moments generated by the lower limb muscles can reduce foot displacement and potentially minimize the chance of experiencing a fall (Brady et al. 2000; Moyer et al. 2009).

The activation of intrinsic foot muscles assists with foot stabilization during initial contact and toe off and proper distribution of force during gait, however their role in successful balance recovery from a slip has yet to be explored (Reeser et al. 1983; Zelik et al. 2015). Furthering our understanding of intrinsic foot muscle activation may provide insight into the existing fall prevention strategies. The presence of a common foot disorder such a Hallux Valgus, may increase the probability of experiencing a slip related fall due to altered muscle mechanics that can negatively influence balance (Hurn et al. 2015; Glasoe 2016). Investigation of the muscle activity within a small subset of this population, when experiencing a slip related perturbation, may help further our understanding of the role of intrinsic foot muscles during balance recovery.

The following chapter will provide an in-depth analysis of the current literature focused on the biomechanics of normal gait (2.1), Hallux Valgus (2.2), the biomechanics of slips and balance recovery (2.3), and the muscular contribution of balance recovery (2.4) which assisted in providing rationale for this study (2.5) and led to the development of the methodology. The final sections of the following chapter will present the purpose and hypotheses (2.6) for this research as well as experimental protocol (3.0) with the objective of gaining a better understanding of the muscular contribution from the lower leg and foot during slip recovery.

2.0 Literature Review

2.1 Biomechanics of Normal Gait

To identify disturbances during normal gait, it is important to thoroughly understand the characteristics of a normal gait pattern. The current literature examining slip perturbations focuses on environmental factors such as the shoe-floor interface and biomechanical factors such as gait characteristics (i.e., step length, gait velocity), kinematics (i.e., lower limb joint angles, velocities, and accelerations), kinetics (i.e., vertical forces, anterior-posterior shear forces, and joint moments), muscle activity, and centre of mass base of support (COM-BOS) relationship (Redfern et al. 2001). A ratio consisting of the horizontal (F_H) and vertical (F_V) components of the frictional force (F_H/F_V) exerted between the shoe-floor interface is maintained during normal gait (Perkins and Wilson 1983; Lockhart 2013). If the magnitude of the F_H/F_V ratio exceeds the coefficient of friction between the shoe-floor interface a slip will likely occur (Lockhart et al. 2005). In other words, if the shear forces generated exceed the coefficient of friction of the shoe-floor interface, then a slip is inevitable (Redfern et al. 2001). Since the shear forces are highest at heel contact and toe off events of the gait cycle this is when a slip is most likely to occur (Redfern and DiPasquale 1997; Redfern et al. 2001). It may be important to note that previous literature has reported that the slips associated with the greatest risk of falling occur at heel contact (Redfern et al. 2001; Moyer et al. 2009). However, slips at toe off may also present a significant risk of falling due to the sudden disturbance of balance, as the static coefficient of friction is exceeded while propelling the body forward (Lockhart 2013). Because these two gait events demonstrate the most significant shear forces during gait, it will be important to examine these key events in depth by making comparisons during level walking and slip perturbations (Redfern and DiPasquale 1997; Redfern et al. 2001).

The gait cycle consists of seven major events: initial contact, opposite toe off, heel rise, opposite initial contact, toe off, feet adjacent, and tibia vertical and can be divided into two major phases, stance and swing (Figure 1) (Whittle et al. 2012). Stance phase lasts from initial contact to toe off, while swing phase lasts from toe off to the next initial contact (Whittle et al. 2012). Gait characteristics such as gait velocity and step length are highly individualized and vary from person to person. Typical self-selected gait velocity has been reported to range from 0.97-1.51m/s (Redfern and DiPasquale 1997; Redfern et al. 2001). Both gait velocity and step length can influence the probability and severity of experiencing a slip perturbation (Moyer et al. 2006). When gait velocity and step length are increased, the ratio of shear forces to the coefficient of friction at initial contact will change, leading to a greater shear force that will likely result in a slip (Redfern et al. 2001). Adopting a more 'cautious' gait pattern (E.g. reductions in step length, flatter foot angle at initial contact) with the goal of reducing the magnitude of shear force has been identified as a useful strategy when a slippery environment is known or with exposure to prior slip experience (Cham and Redfern 2002; Marigold and Patla 2002; Moyer et al. 2006; Heiden et al. 2006).

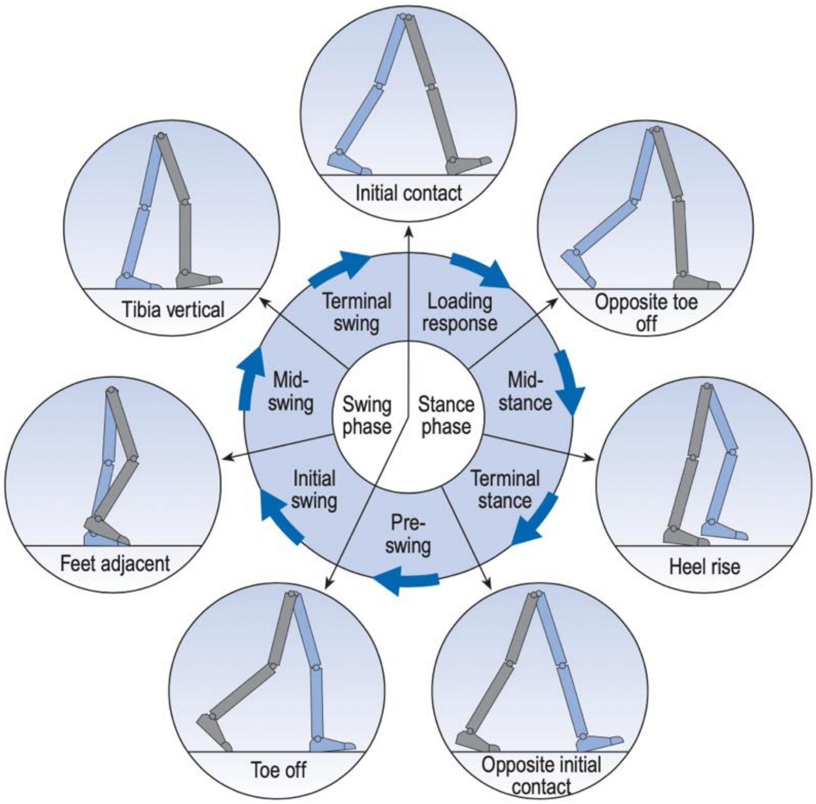


Figure 1: Positions of the legs during a single gait cycle by the right leg (grey leg) (Whittle 2007) (Reprinted with permission from Elsevier)

2.1.1 Ground Reaction Forces

Force plates are commonly used in biomechanical research, such as gait analysis, and are used to measure ground reaction forces and to assist in identifying gait cycle timing (Hall 2012). The ground reaction force is made up of three components of force: the vertical force, anterior-posterior force, and medial-lateral force (Hall 2012; Whittle et al. 2012). The vertical force has a characteristic bimodal shape, which is a result of changes in the acceleration of the centre of mass during the stance phase. The first peak represents the upward acceleration of the centre of mass shortly after heel contact when body weight is being transferred onto the leading limb for support. The dip in the vertical force is a result of a reduction in downward force during the transition into midstance. The second peak is due to the deceleration as the downward motion transitions into late stance prior to toe off (Figure 2) (Whittle et al. 2012). The anterior-posterior force, also referred to anterior-posterior (AP) shear force, exhibits a negative deflection which indicates ‘breaking’ force, following heel contact until the end of midstance followed by a positive deflection which indicates ‘propulsion’ until toe off (Figure 2) (Whittle et al. 2012). Lastly, the medial-lateral force during gait typically has a decreased magnitude compared to the previously discussed ground reaction forces, characterized by a small peak in the lateral direction at initial contact, followed by the acceleration of the centre of mass medially until to off (Figure 2) (Whittle et al. 2012). As stated previously, these ground reaction forces are dependent on characteristics of gait (i.e., step length, gait velocity, ankle angle) (Cham and Redfern 2002; Moyer et al. 2006; Heiden et al. 2006). Deviations from normal characteristics, such as an increased step length due to the demands of the environment will result in an increased or decreased probability or severity of experiencing a slip.

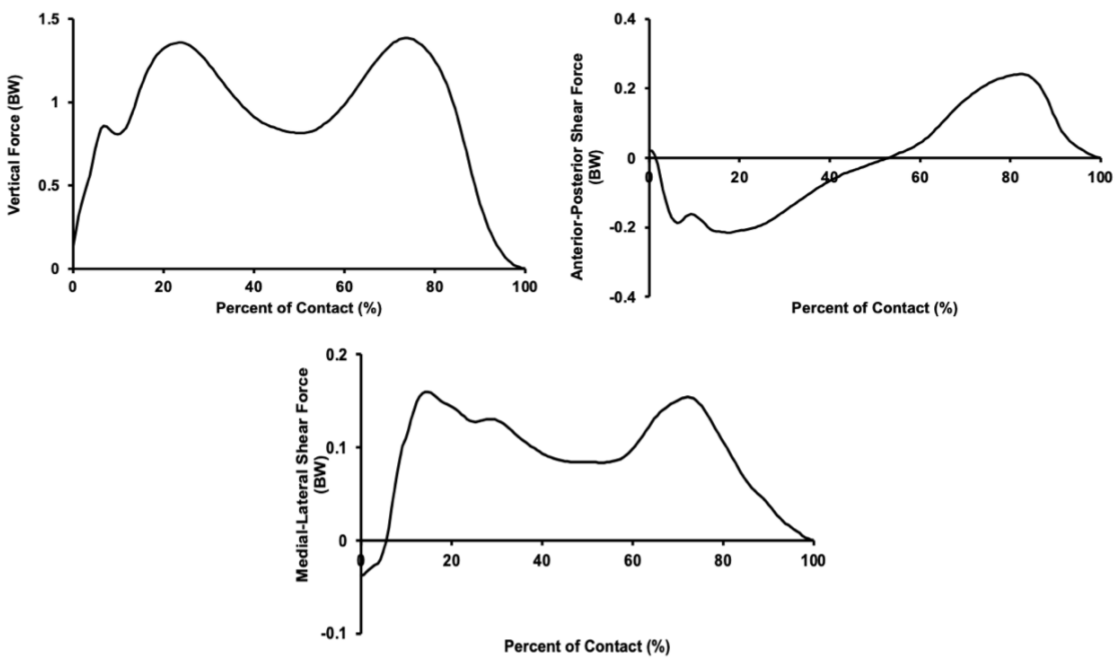


Figure 2: Right leg ground reaction forces (normalized to body weight (BW;kilograms*9.81m/s^2) in the vertical (top left), anterior-posterior (top right), and medial-lateral (bottom) directions during the single stance phase (contact) with the force plate.

2.1.2 Joint Angles

During gait the ankle, knee, and hip joints go through a range of motion within the sagittal plane (Figure 3). At heel contact, the ankle is in slight dorsiflexion before swiftly transitioning into a plantarflexion moment, as the foot rotates flat onto floor. The ankle joint goes into plantarflexion again when toe off phase begins (Redfern et al. 2001). When anticipating a slippery floor, changes in the ankle angle at initial contact have been observed. A significant decrease in the foot angle (foot-floor angle) at initial contact has been reported to be a proactive strategy to minimize the severity of a slip (Heiden et al. 2006). Additionally, a reduction in peak moments at the ankle in an attempt to decrease the magnitude of shear forces, minimizing the probability of a slip (Cham and Redfern 2002). During the first 30% of stance, an increased flexion of the knee caused by the forward rotation of the shank (lower leg) can be observed. Towards the end of stance as the centre of mass moves past the limits of the single leg base of support, the knee goes into flexion again in preparation for heel contact of the contralateral limb and toe off of the supporting limb (Redfern et al. 2001). The hip angle depends on changes in thigh orientation so during stance, the hip is in extension as a result of the continuous forward rotation of the thigh. At the end of stance, the preparation for swing phase occurs resulting in hip flexion due to the plantarflexion moment at the ankle and subsequent flexion at the knee (Redfern et al. 2001).

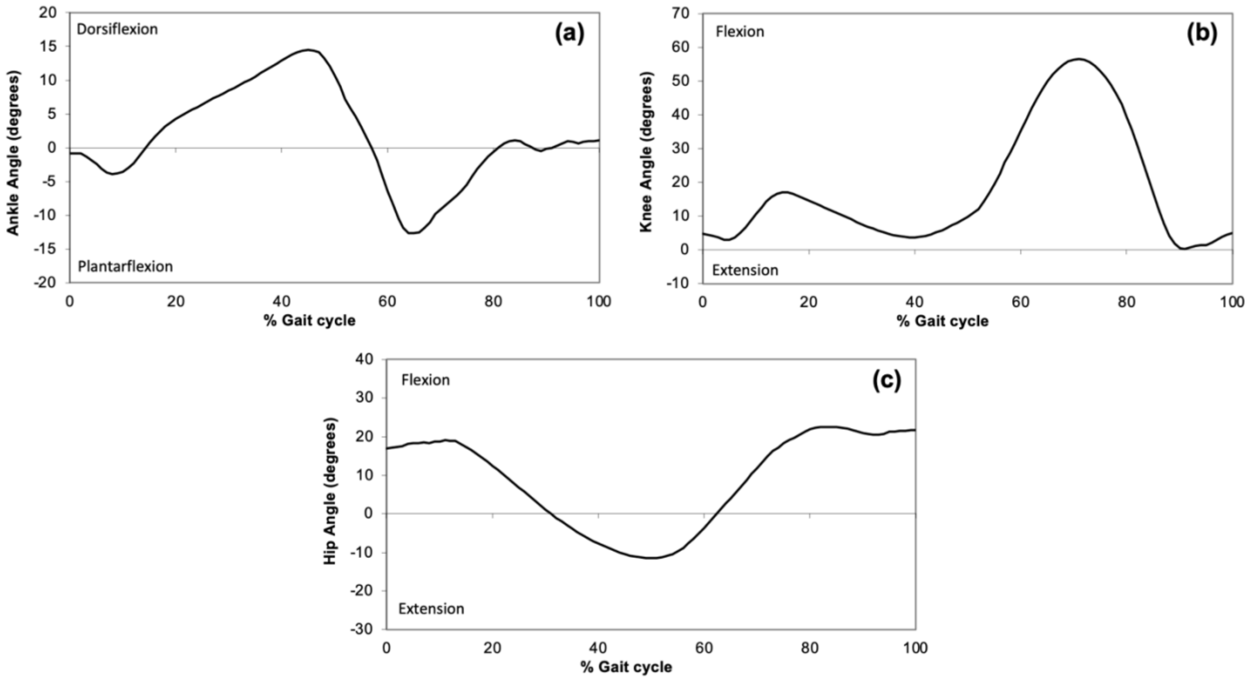


Figure 3: Right leg sagittal plane joint angle profiles during the gait cycle (a) ankle (+dorsiflexion, - plantarflexion), (b) knee (+ flexion, - extension), and (c) hip (+ flexion, - extension)

2.1.3 Muscle Activity

The coordination of activation patterns within lower limb muscles makes it possible for movement at the hip, knee, and ankle joints during gait. Current gait and slip perturbation literature have examined the activation timing, duration, and magnitude of hip, thigh, and superficial lower leg musculature thoroughly (Tang et al. 1998; Marigold et al. 2003; Whittle et al. 2012; O'Connell et al. 2016). The role of intrinsic foot muscles has been explored during static stance, with limited knowledge on their activation timing, duration, and magnitude during gait (Kelly et al. 2012; Zelik et al. 2015; Robb et al. 2021). Although hip and thigh musculature are important during gait, the focus for the rest of this section will be on describing the role of lower leg and intrinsic foot muscles during gait.

At initial contact, the tibialis anterior begins to work eccentrically to control foot fall as the body transitions into double support (Hunt et al. 2001; Murley et al. 2009b). Peroneus longus works with the tibialis anterior after initial contact to evert the foot, stabilizing the ankle joint during early stance (Hunt et al. 2001). Flexor hallucis longs also assists ankle stabilization prior to the forefoot making contact with the ground (Knox et al. 2021). Tibialis posterior is active during the contact and midstance phase of gait and is suggested to work in a synergistic role with peroneus longus to stabilize the hindfoot (Murley et al. 2009a). During propulsion, peroneus longus counteracts inversion for ankle stabilization while flexor hallucis longus is active simultaneously to continue to propel the body forward (Hunt et al. 2001; Zelik et al. 2015). The tibialis anterior is also active following propulsion to bring the ankle into dorsiflexion and ensure the foot clears the ground in swing (Whittle et al. 2012; Zelik et al. 2015).

The intrinsic foot muscles have been reported to assist in stabilizing the foot during gait (Wong 2007; Kelly et al. 2012; Zelik et al. 2015). The transverse head of adductor hallucis exhibits peak activity at initial contact to stabilize the metatarsal heads (Robb et al. 2021). Abductor hallucis is active in the late stance and toe off phase of gait, while also acting as a dynamic stabilizer for the medial longitudinal arch (Reeser et al. 1983; Wong 2007). Extensor hallucis brevis produces metatarsophalangeal extension around foot-lift to prepare the foot for toe off (Zelik et al. 2015). The transverse head of adductor hallucis is active again at toe off to aid in forefoot stabilization and anchor the first toe during propulsion (Robb et al. 2021).

2.2 Hallux Valgus

Hallux Valgus (HV) is a functional deformity that leads to foot pain, impaired gait patterns, and poor balance (Menz and Lord 2001, 2005; Cho et al. 2009; Hurn et al. 2015). HV is characterized by the lateral deviation of the first toe at the metatarsophalangeal (MTP) joint affecting the anatomical orientation, potentially resulting in altered mechanics of the intrinsic and extrinsic muscles of the foot (Hurn et al. 2015; Glasoe 2016). Typically, an overgrowth of bone called a bunion can form accompanying the HV deformity (Menz et al. 2011; Glasoe 2016). HV can be assessed by the HV angle, defined by the angle between the longitudinal axis of the first metatarsal and the longitudinal axis of the proximal phalanx of the hallux (Hurn et al. 2015). The HV angle can be measured clinically through the use of digital radiography however, this method can be time consuming and expensive (Menz et al. 2010). HV is generally considered to be present when the HV angle is 15˚ or greater (Garrow et al. 2001; Menz et al. 2010). The Manchester Scale is an alternative method that assesses the severity of HV and has been proven to be a valid and reliable non-invasive tool (Menz et al. 2010). The Manchester Scale consists of four standardized photos displaying varying degree of HV deformity (none, mild, moderate, and severe) (Garrow et al. 2001).

A common symptom of HV is pain located at the first MTP joint which can be associated with soft tissue damage and/or pressure from ill-fitting footwear (Cho et al. 2009; Menz et al. 2011; Kim et al. 2013). Individuals with HV are more likely to report pain in the foot and other body regions such as the low back, hip, and knee which may indicate that HV is mechanically affecting joints through the kinetic chain (Menz et al. 2011). A review article by Nix et al. (2010) discovered through a meta-analysis by age subgroups that there is a 23% prevalence of HV in adults aged 18 to 65 and an observed increase in the prevalence as age progressed (Nix et al. 2010). It is important to note that although peak onset of HV is from 30 to 60 years of age, it is highly likely that initial changes develop during adolescence or even earlier, classified as juvenile HV (Piggott 1960; Coughlin 1995).

Within the current literature the etiology of HV is still unknown. However, there are a variety of both environmental and biological factors that have been suspected to lead to the progression of the deformity. Footwear and excessive loading are environmental factors that are potentially linked to the progression of HV (Coughlin 1995; Kernozek et al. 2003; Cho et al. 2009; Glasoe 2016). Unshod populations have a very low prevalence of HV compared to shoe-wearing populations. Footwear characteristics such as a narrow toe box or a high heel cause increased pressure and loading within the forefoot exacerbating the HV deformity (Cho et al. 2009). Since HV can slowly progress overtime, it has been suggested that repetitive loading of the MTP joint due to occupation, excessive walking, and/or increase in weight-bearing activities can continue to influence HV. However, a review of the current literature by Perera et al. (2011) revealed that a clear link between these environmental factors has not been established so future work may need to focus in on the relationship of these factors to HV progression (Perera et al. 2011).

A genetic predisposition to developing HV is one of many biological factors indicating causation of the HV deformity. HV has been found to be more common in females with the suspicion of a maternal link (Coughlin 1995; Coughlin and Jones 2007; Atbaşı et al. 2020). Other factors such as ligamentous laxity and first ray hypermobility are more common in women, which contributes to the high prevalence of HV observed in females (Coughlin and Jones 2007; Kim et al. 2013; Dullaert et al. 2016). Finally, foot posture, specifically pes planus has largely been associated with HV as pronation increases forefoot loading thus, putting stress on the first MTP joint (Atbaşı et al. 2020).

HV deformity can lengthen and shorten muscles that insert on the first toe, reducing their ability to produce or sustain force (Iida and Basmajian 1974; Glasoe 2016). This imbalance can be detrimental to balance, specifically within the intrinsic foot muscles since they act as dynamic stabilizers (Wong 2007; Kelly et al. 2012; Zelik et al. 2015). It has been observed that individuals with HV have an imbalance of the adductor hallucis and the abductor hallucis (AbdH) muscles with this imbalance being a likely reason for joint deformity (Kim et al. 2013) (Figure 4). The activity of AbdH during abduction of the first MTP joint was significantly decreased compared to the activity of adductor hallucis during adduction of the first MTP joint in individuals with HV (Iida and Basmajian 1974; Kim et al. 2013). The anatomical nature of adductor hallucis has been the focus of clinical interest as it plays a role when surgically correcting the HV deformity (Arakawa et al. 2003). There is some anatomical variability of the adductor hallucis muscle within the transverse head as the insertion of the muscles can laterally displace the proximal phalanx resulting in the tendon of the transverse head being frequently released to correct HV, indicating that the transverse head of adductor hallucis is a key muscle in joint deformity (Arakawa et al. 2003). Muscles that support the medial longitudinal arch are important to examine as pronation is often observed in individuals with HV, suggesting that the muscles supporting the medial longitudinal arch are no longer functioning effectively (Eustace et al. 1994; Fiolkowski et al. 2003; Wong 2007; Dullaert et al. 2016). Individuals with HV had an earlier onset of intrinsic muscle activity at heel strike, which indicated a potential attempt to stabilize a hypermobile first ray (Fiolkowski et al. 2003; Wong 2007). However, it was noted that there is limited knowledge of the muscle activity within HV individuals which may be due to the difficulties associated with recording muscle activity of the intrinsic foot muscles, specifically in a dynamic situation. There is a large opportunity for cross-talk of muscles when using surface electromyography as well as the potential for gait modifications due to discomfort from fine wire electromyography (Iida and Basmajian 1974). It is important to gain a better understanding of the muscle activity in individuals with HV during dynamic activities such as gait, since these individuals are at risk for balance problems.

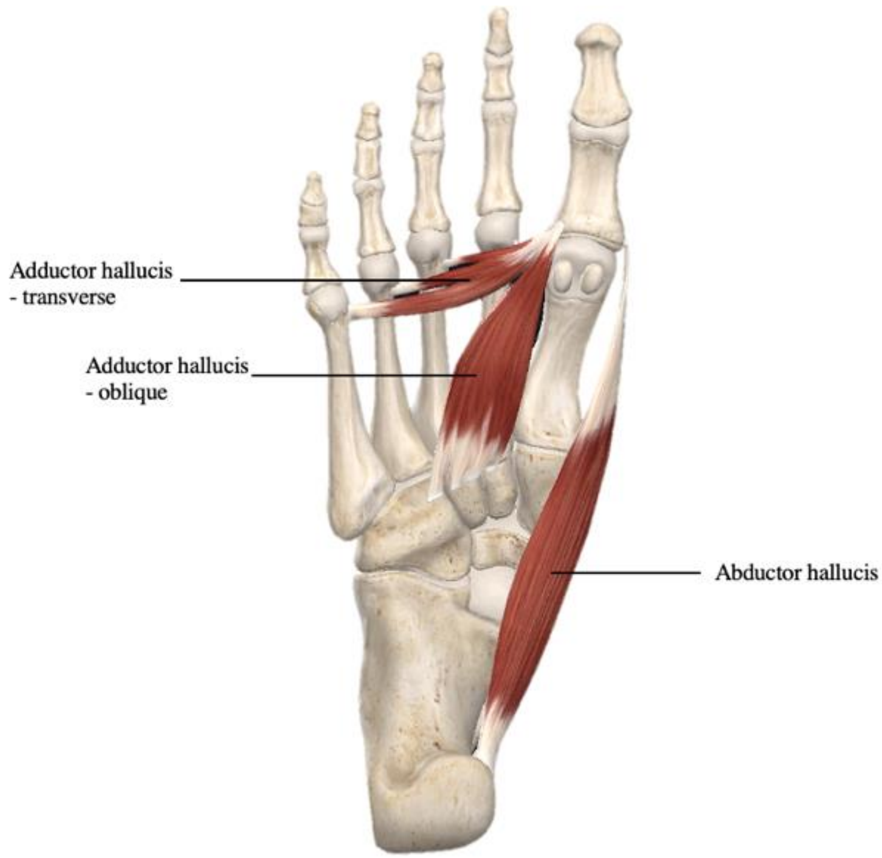


Figure 4: The anatomy of adductor hallucis (AddT) and abductor hallucis (AbdH) viewed from the plantar surface in a normal foot (3D4Medical Ltd for Complete Anatomy Version 8.0.1, 2021). (Reprinted with permission from Elsevier and 3D4Medical).

2.3 The Biomechanics of Slips and Balance Recovery

Falls are a result of inadequate recovery responses when reacting to an unexpected perturbation and are a major cause of injury in everyday life (Marigold et al. 2003). A 2004 Health Report published by Statistics Canada revealed that slipping on a non-icy surface accounted for 42% of falls for individuals aged 12 to 64 (Wilkins and Park 2004). Gait is a common dynamic task of everyday living and is used to propel humans through their environment. During gait, the transition from swing to stance during heel contact is when individuals are most vulnerable to an unexpected gait perturbation such as a slip (Lockhart et al. 2005; Moyer et al. 2009). A slip can be defined as the heel sliding along a surface shortly after heel contact, resulting in a loss of balance, before coming quickly to a complete stop (Redfern et al. 2001; Lockhart et al. 2005). Slips can be classified based on the distance that the heel travels. Mini-slips are defined as a <1cm distance travelled and an undetected slipping motion, midi-slips are defined as a 3-5cm distance travelled and a slip-recovery without a major gait disturbance, and maxi-slips are defined as <8cm distance travelled and a slip-recovery with a large corrective response, almost resulting in a total loss of balance. Slips that are likely to result in a fall if the distance travelled exceeds 10cm or if the peak velocity is greater than 0.5m/s (Strandberg 1983; Redfern et al. 2001). Other factors that contribute to slip severity include walking style (E.g. step length, cadence, coefficient of friction, heel contact angle, velocity and acceleration) (Brady et al. 2000; Lockhart et al. 2003; Moyer et al. 2006; Beschorner and Cham 2008) and the state of the perturbed foot at slip initiation and the subsequent corrective reactions that are generated in response to regain balance (Moyer et al. 2006).

When a slip perturbation is experienced, deviations in vertical force, knee angle, and knee angular velocity is significant with an earlier onset of 70-110ms compared to normal (Beschorner et al. 2013). This suggests that somatosensory feedback from the foot and joint velocity may be critical in executing a quick postural response. Corrective reactions generated by the perturbed/leading limb are thought to be of most importance consisting of a reduced extension moment at the knee followed by an increased extensor moment at the hip in an attempt to slow down the forward trajectory of the COM and regain balance (Cham and Redfern 2001; Moyer et al. 2009). Once the slip is initiated, heel strike angle as well as foot displacement and velocity within the perturbed limb may influence the severity of the slip (Brady et al. 2000). Previous literature has reported that a slip related fall is likely to occur when the displacement and velocity of the perturbed limb has exceeded 10cm and 0.5m/s respectively (Strandberg 1983;

Redfern et al. 2001). However, recovery from a slip of this magnitude and velocity is possible with the appropriate muscles recruited through reflexive activation to restore balance (Tang and Woollacott 1998; Brady et al. 2000). These current values seem to be too conservative and do not accurately represent the maximum displacement or velocity in which recovery from a slip perturbation is possible (Brady et al. 2000). Further investigation of other factors such as the role of the trailing limb as well as the activation patterns of the deep muscles within the lower leg and the intrinsic foot muscles may be important for understanding critical elements of successful balance recovery.

Although much of the current literature focuses on the perturbed/leading limb during a slip perturbation, the coordination of the trailing limb with the perturbed limb has potential in assisting successful balance recovery from a slip (Cham and Redfern 2001; Moyer et al. 2009; O'Connell et al. 2016). The swing phase of the trailing leg is typically interrupted during a slip and this response can be compared to a stepping response during stance, widening the base of support and regaining stability (Moyer et al. 2009; O'Connell et al. 2016). Moyer et al. (2009) categorized trailing leg responses to slips into four types of strategies: minimum, foot-flat, mid-flight, and toe-down depending on the flight distance, flight duration, and position of the foot at contact following the initiation of the slip. Minimum strategies mimicked a similar trajectory of the trailing limb during normal gait whereas the other three strategies (foot-flat, mid-flight, and toe-down) interrupted the swing phase of the trailing limb and were only observed during severe slip perturbations (Moyer et al. 2009). Trailing limb corrective strategies occurred immediately following the onset of the perturbed/leading limb's response (Moyer et al. 2009; O'Connell et al. 2016). Thigh muscle activity from the medial hamstring and vastus lateralis of the trailing limb was reported to be modulated by the severity of the slip (O'Connell et al. 2016) assisting with specific strategies implemented depending on the need for stability in a certain direction (medial-lateral or anterior-posterior), playing a role in determining ideal foot placement for a compensatory stepping reaction (Maki and Mcllroy 1999; Moyer et al. 2009).

2.4 Muscular Contribution of Balance Recovery

Successful balance recovery from a slip involves the initiation of extrinsic foot muscles about the ankle, similar to an ankle strategy observed when static balance is disturbed (Runge et al. 1999; Moyer et al. 2006). Extrinsic foot muscles such as the tibialis anterior (TA), tibialis posterior (TP), flexor hallucis longus (FHL), and peroneus longus (PL) have muscle bellies located within the anatomical leg and control balance through motion about the ankle joint (Glasoe 2016). This group of muscles have long tendons that cross both the ankle and MTP joints, aiding in the flexion and extension of the toes, which is important during key phases of gait such as toe off (McKeon et al. 2015; Zelik et al. 2015). TA is known as the main dorsiflexor and controls the foot in an eccentric contraction during heel contact (Hunt et al. 2001; Murley et al. 2009b). When exposed to a slip, a reduction in the moment about the ankle, indicating plantarflexion, may be a strategy to reduce the distance the perturbed limb travels and recover balance quicker (Redfern et al. 2001). TP is an inverter of the hindfoot, most active during the contact phase and midstance phase of gait (Murley et al. 2009a). It also supports the transition from an inverted foot position to a more neutral foot position during midstance, preventing the medial longitudinal arch from collapse (Gray and Basmajian 1968; Hunt et al. 2001). FHL is active during the loading period of initial contact acting as an ankle stabilizer prior to the forefoot contacting the ground (Knox et al. 2021). FHL is responsible for ankle and first toe flexion, making it a key muscle during toe off (Kirane et al. 2008; Zelik et al. 2015). PL has an important role everting the rear foot, aiding in stabilization of the ankle joint following initial heel contact (Hunt et al. 2001).

Lower limb muscle activity contributing to joint moments and postural adjustment strategies assist in determining if the outcome of a slip perturbation will result in successful balance recovery or a fall (Tang et al. 1998; Redfern et al. 2001; Cham and Redfern 2001; Chambers and Cham 2007; Moyer et al. 2009). Muscle activation patterns are dependent on the direction of the perturbation experienced, such as during a perturbation, the ankle joint may deviate from normal towards plantarflexion so the tibialis anterior muscle may exhibit increased magnitude to counteract this joint moment. This suggests that when joint angle position deviates from normal, corrective reactions are generated from muscles distal to proximal to restore joint position (Nashner 1980; Tang et al. 1998). Activation within the anterior lower leg muscles with simultaneous thigh muscle activation assisted in maintaining forward gait progression and minimal changes in gait velocity, resulting in regaining balance control (Tang et al. 1998). Some corrective strategies involve an increase of knee flexion and hip extension, occurring on average between 190 and 350ms after heel contact in an attempt to bring the perturbed foot closer to the body (Cham and Redfern 2001). Muscle activation patterns within the perturbed/leading limb during initial detection of a slip consisted of activation of the medial hamstring followed by the tibialis anterior, then the medial gastrocnemius, and finally the vastus lateralis (Chambers and Cham 2007). This muscle latency pattern follows a reactive response consisting of primary knee flexion followed by a proactive strategy of knee extension. This finding was consistent with joint moments observed within previous literature (Cham and Redfern 2001; Chambers and Cham 2007). The role of the ankle joint seemed to be minimal, with the observation of a reduced plantarflexion moment with the severity of the slip (Cham and Redfern 2001). Results from this study seem to contrast previous literature (Horak and Nashner 1986; Runge et al. 1999) and suggest that slipping elicits varying postural strategies involving a combination of joints that may be dependent on factors at the onset of a slip, such as gait timing (E.g. during weight transfer from initial contact to mid-stance) and the characteristics of the shoe-floor interface (Cham and Redfern 2001). Other studies have revealed the importance of ankle musculature during successful balance recovery from a slip. Increased power (muscle force*velocity) within the tibialis anterior muscle during a slip perturbation has been observed and this activation is suggested to result in a delay of foot flat during mid-stance, which may slow forward velocity of the slipping limb and aid in the continuation of gait (Chambers and Cham 2007). Differing activation of the tibialis anterior in combination with adjusting the reactive response depending on the slip severity suggest that increased activity in the lower limb results in the presence of ankle muscle co-contraction at heel contact and aid in the control of foot positioning (Cham and Redfern 2001; Chambers and Cham 2007). Later onset of medial gastrocnemius within the sequence of lower limb activation patterns may result in experiencing a less severe slip and increasing the chances of successful recovery. Increased magnitude of medial gastrocnemius around heel contact results in a reduced foot-floor angle during initial contact which is a reported adaptation when the conditions of the environment (anticipating slippery floors) is known (Marigold and Patla 2002; Chambers and Cham 2007). Muscle activation patterns within the lower limb of the perturbed/leading limb demonstrate the importance of the knee joint and surrounding musculature in successful balance recovery. It is important to continue to examine the ankle joint during recovery from a slip perturbation to determine its role in reactive balance strategies. Additionally, continuing to examine differences in joint moments and muscle activation patterns during proactive balance strategies, when the condition of the environment is known, compared to reactive strategies may further our insight on balance control overall.

Dynamic balance control during gait is largely maintained by the extrinsic foot muscles however, weakness within the intrinsic foot muscles can result in balance impairments (Menz et al. 2005; Kelly et al. 2012). The intrinsic foot muscles are located within the foot and play an important role in stabilizing the foot during gait (Fiolkowski et al. 2003; McKeon et al. 2015). The additional activation of the plantar intrinsic foot muscles specifically, function as shock absorbers during late stance and assist in reducing stress on the plantar fascia (Okamura et al. 2018). This group of muscles serve as functional structures adapting their recruitment depending on the demands of the situation (Kelly et al. 2012; Zelik et al. 2015), thus it can be theorized that this group of muscles are important for balance recovery when exposed to a slip perturbation. The adductor hallucis is responsible for adducting the first toe at the MTP joint and is comprised of an oblique and a transverse head (Arakawa et al. 2003). Due to the role that the transverse head of adductor hallucis (AddT) has within the HV deformity as mentioned previously, this portion of the muscle will be the focus moving forward when referencing AddT (Arakawa et al. 2003). The abductor hallucis (AbdH) is located on the medial aspect of the foot and maintains first MTP joint stability by preventing abnormal transverse plane motion through an isometric contraction (Stewart et al. 2013). As the HV deformity progresses, an imbalance between AddT and AbdH develops. AddT assists in the deviation pulling the proximal phalanx medially (Arakawa et al. 2003). The anatomical relationship of AbdH with the first MTP joint shifts to the plantar aspect of the toe, resulting in a loss of abductor function but with a gain in flexor force (Arinci İncel et al. 2003; Stewart et al. 2013). Extensor hallucis brevis (EHB) is located on the dorsal aspect of the foot, displaying peak activity prior to propulsion as this muscle is the main extensor of the proximal phalanx (Zelik et al. 2015). Previous EMG studies focused on intrinsic foot muscles revealed that the recruitment pattern of EHB during gait significantly varied between participants, with some individuals displaying no muscular activity (Zelik et al. 2015). Considering the insertion of EHB on the dorsal aspect of the proximal phalanx of the first toe, its role in HV may be significant. The HV deformity causes the axis of EHB to shift laterally, transitioning its role from an extensor to an adductor of the first toe which is another instance of muscle mechanics that are altered by HV (Alvarez et al. 1984). During gait, the foot experiences deformation to structures such as the medial and transverse arch of the foot (Zelik et al. 2015; Nakai et al. 2019). These arches are supported mostly by the intrinsic foot muscles ensuring proper force transmission to continue forward momentum. However, if these muscles are weakened by HV, then these structures are no longer functioning efficiently resulting in altered gait mechanics and pain (Nakai et al. 2019).

The transverse and medial longitudinal arches of the feet play an important functional role during dynamic movement by supporting weight and absorbing impact (Mulligan and Cook 2013; Nakai et al. 2019). The transverse arch is located within the forefoot region and is directly involved with the HV deformity (Nakai et al. 2019). A weakening of AddT has been observed in HV individuals, which can be speculated to result in a collapse of the transverse arch. If there is a weakened muscle responsible for forming the transverse arch structure, then insufficient force transmission may occur during gait causing mechanical stress on the foot (Nakai et al. 2019). The medial longitudinal arch is actively supported by extrinsic and plantar intrinsic muscles working in a synchronized manner to control stresses on the foot during gait (Kelly et al. 2012; Mulligan and Cook 2013). Foot pronation signifies a loss of height in the medial longitudinal arch and is a common foot posture in individuals with HV (Eustace et al. 1993; Atbaşı et al.

2020). It has been reported that reduced muscle activity within AbdH relates to medial longitudinal arch deformation, such as collapse from excessive pronation (Kelly et al. 2012). It is important to note that the muscle activity of AbdH is decreased in the presence of HV, further exacerbating pronation resulting in poorer shock absorption from the medial longitudinal arch and impairing gait (Iida and Basmajian 1974; Kim et al. 2013).

2.5 Rationale for this Study

The risk of experiencing a slip resulting in a fall or serious injury in everyday life is very likely and impacts individuals of all ages (Wilkins and Park 2004). Reactive responses generated by the thigh and lower leg muscles result in gross movements that prevent the outcome of a slip perturbation resulting in a fall (Tang et al. 1998; Cham and Redfern 2001; Chambers and Cham 2007; Moyer et al. 2009). Lower leg muscles, such as the tibialis anterior, are responsible for generating corrective actions about the ankle, to restore balance and maintain a forward progression of gait following a slip perturbation. Previous literature has suggested that intrinsic foot muscles provide additional stabilization assisting dynamic balance control (Fiolkowski et al. 2003; Kelly et al. 2012; McKeon et al. 2015; Zelik et al. 2015) and may serve an important role in reactive balance control following a slip perturbation. However, the presence of Hallux Valgus, a common foot disorder, leads to anatomical differences and can result in altered muscle mechanics of both the lower leg and foot musculature, increasing the probability of experiencing a slip related fall (Cho et al. 2009; Nix et al. 2010; Menz et al. 2011; Hurn et al. 2015). Thus, investigation of the balance responses within an unaffected and affected population when experiencing a slip perturbation may provide insight into the existing fall prevention strategies.

2.6 Purpose and Hypotheses

The purpose of this study was to examine the lower leg and foot muscular activity during slip recovery in individuals with unaffected feet and those with Hallux Valgus. The muscular activity of select extrinsic and intrinsic muscles using electromyography (EMG) during level walking will be compared to the muscle activity during an unexpected slip. This insight may reveal the key muscle activity for a successful balance response. Changes such as timing and magnitude of muscular activity, three-dimensional motion about the ankle joint, and shear forces at the heel across multiple time points may demonstrate these differences. Balance control will also be assessed using three-dimensional motion capture and force plates during level walking and when exposed to unexpected slips.

It can be hypothesized that:

1) During a heel contact slip perturbation, the extrinsic muscles will exhibit earlier onsets and greater magnitudes in the perturbed limb EMG activity. Specifically, earlier onsets of the tibialis anterior, tibialis posterior, and peroneus longus compared to level walking trials. Flexor hallucis longus will exhibit a later onset and diminished magnitude compared to level walking trials. The intrinsic muscles, specifically adductor hallucis, abductor hallucis, and extensor hallucis brevis, will also exhibit earlier onsets and greater magnitudes in the perturbed limb EMG activity compared to level walking trials to stabilize the foot and grip the ground to prevent any further forward translation. This hypothesis will be examined by analyzing the timing and magnitudes of lower leg and foot muscle activity during unexpected slip trials compared to normal gait trials prior to experiencing a slip perturbation.

2) During a heel contact slip perturbation, individuals with Hallux Valgus will exhibit diminished magnitudes within the extrinsic and intrinsic foot muscles of the perturbed limb, compared to individuals with unaffected feet due to the altered muscle mechanics. However, these magnitudes will be greater compared to level walking trials. In general, onset of the extrinsic and intrinsic muscles of the perturbed limb will occur earlier compared to level walking trials. This hypothesis will also be examined by analyzing the timing and magnitudes of lower leg and foot muscle activity during unexpected slip trials compared to normal gait trials prior to experiencing a slip perturbation.

3) Reactive balance control in individuals with Hallux Valgus will be diminished compared to unaffected individuals due to changes muscle mechanics. This hypothesis will be examined by analyzing changes in COM velocity in the anterior-posterior and vertical directions during the single stance phase of normal gait trials versus unexpected slip trials.

3.0 Methods

3.1 Participants

Twenty young adults (age: 24.15 ± 1.57 years; weight: 72.98 ± 12.47kg; height: 172.55 ± 7.79cm) consisting of individuals with unaffected feet (n=16; 10 males, 6 females) and those with Hallux Valgus (n=4; 4 females) were recruited from a university population using poster advertisements and word of mouth. All procedures were approved by the institutional Research Ethics Board at Wilfrid Laurier University (REB#6983). A screening questionnaire and the Manchester scale (to assess the severity of Hallux Valgus (bunion)) was provided electronically to all prospective candidates and was used to exclude individuals with $<15^{o}$ or $>30^{o}$ of Hallux Valgus (Photo A or Photo D on the Manchester Scale, Figure 5) or with known neurological and/or musculoskeletal disorders (see Screening Questionnaire in Appendix A). The Manchester Scale was used to self-assess the severity of the bunion (Figure 5). This scale consists of standardized photos of the forefoot that identifies four degrees of Hallux Valgus. Upon determining that the volunteer qualifies for this study they were invited to participate. Prior to the start of the initial testing session all participants were required to read and sign an informed consent; any questions related to the research protocol were answered at this time. Testing was completed in one visit lasting approximately 1.5-2 hours.

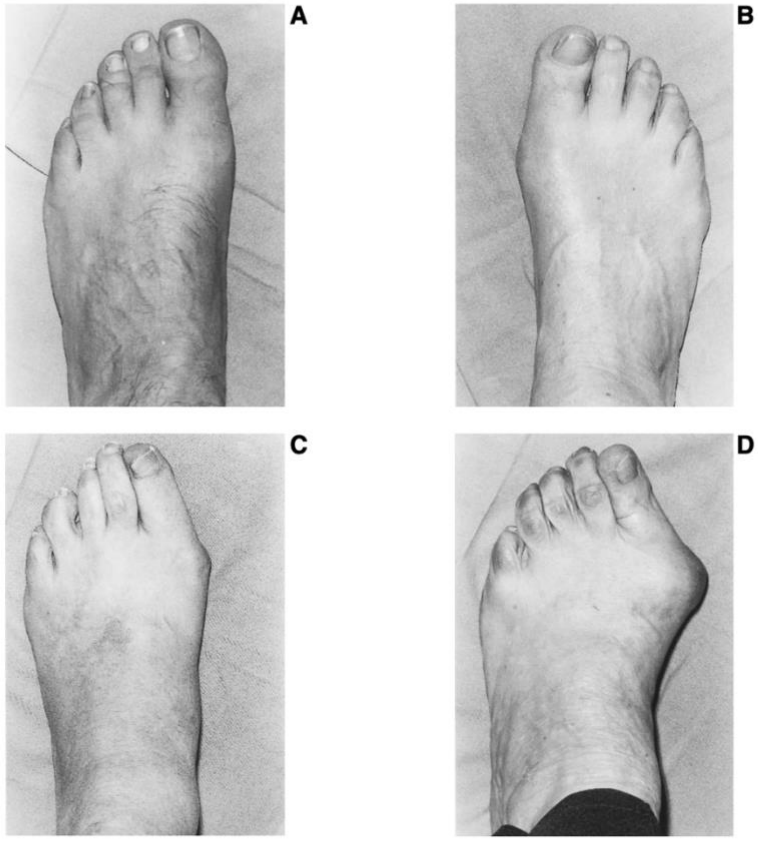


Figure 5: The Manchester Scale from Garrow et al. 2001; Hallux Valgus grading photographs. A – Grade 1 (no deformity), B – Grade 2 (mild deformity), C – Grade 3 (moderate deformity), and D – Grade 4 (severe deformity). (Reprinted with permission from the Journal of American Podiatric Medical Association).

3.2 Experimental Protocol

Upon arrival to the laboratory, the Manchester Scale was repeated to confirm self-reported bunion severity. Semmes-Weinstein monofilaments (North Coast Medical, Inc., Morgan Hill, CA) were used to assess plantar-surface sensation of the foot (calcaneus, fifth and first metatarsal head, and hallux). This was used to quantify cutaneous sensation on the plantar surface of the foot and to ensure all participants had ‘normal’ cutaneous sensation thresholds. Kinematic data was collected using the OptoTrak motion capture cameras (OptoTrak Certus; Northern Digital Inc., Waterloo, Ontario, CAN) and kinetic data with force plates (AMTI OR6-5-2000; Waterdown, Massachusetts, USA). An electromyography (EMG) system (Ultium, Noraxon, USA) was used to collect fine-wire intramuscular and surface electromyography (EMG) of specific lower limb and foot muscles in both legs. Muscle activity was collected from 4 muscles on the perturbed/leading limb via fine-wire intramuscular EMG (adductor hallucis-transverse, extensor hallucis brevis, flexor hallucis longus, tibialis posterior), and 3 muscles via bilateral surface EMG (tibialis anterior, abductor hallucis, peroneus longus), for a total of 10 recordings.

All intramuscular electrode insertions were consistently performed by the same trained electromyographer. All insertion sites were sterilized according to the laboratory's standard operating procedures. Each muscle of interest (adductor hallucis-transverse, extensor hallucis brevis, flexor hallucis longus, tibialis posterior), was identified using real-time ultrasound imaging (SonoSite, M-Turbo, Markham, Canada). The doppler function was used to identify neurovascular bundles within the insertion area and to confirm the depth/location of the muscle of interest. A 15-6MHz linear array transducer (HFL50, SonoSite) was used to guide the intramuscular insertions. The adductor hallucis-transverse was approached from the dorsal aspect of the forefoot. Metatarsal heads II, III, and IV were palpated and landmarked for the insertion into the muscle. The fine-wire electrodes were inserted proximal to the metatarsal heads, through the dorsal interossei muscle between digits III and IV, and as close as possible to the extensor digitorum longus tendon without making contact (Robb et al. 2021). The extensor hallucis brevis was also approached from the dorsal aspect of the foot. The muscle was located by initially palpating the inferior aspect of the lateral malleolus. The fine-wire electrodes were inserted approximately three finger breadths distal to the lower boarder of the lateral malleolus, parallel to the lateral boarder of the foot. The flexor hallucis longus muscle was approached laterally on the posterior aspect of the lower leg. The Achilles tendon was palpated approximately five fingerbreadths above its insertion, anterior to the lateral boarder of the tendon. The fine-wire electrodes were inserted obliquely towards the tibia. Lastly, the tibialis posterior was approached from the medial aspect of the calf, palpating approximately one handbreadth distal to the tibial tuberosity and one finger breath off the medial boarder of the tibia. The fine-wire electrodes were inserted obliquely through the soleus and flexor digitorum longus, posterior to the tibia.

Two 230 Kendall electrodes (Covidien, Mansfield, USA) were placed bilaterally on the tibialis anterior and peroneus longus and two 130 Kendall electrodes were placed bilaterally on the abductor hallucis. All muscle bellies were identified by palpation and while performing a concentric contraction. For example, participants were asked to dorsiflex to identify the tibialis anterior muscle belly. All surface electrodes were placed in the direction of the muscle fibres. Confirmation of electrode placement (fine-wire intramuscular and surface) and signal quality was assessed by performing a resisted contraction for each muscle and observing real-time muscle activity on the collection computer. Twelve IRED markers were placed bilaterally on the third metatarsals, ankles (talus), knees (tibial tuberosity), hips (anterior superior iliac spine), shoulders (acromion process) as well as on the xyphoid and forehead to track segmental as well as whole body motion represented by the centre of mass.

All participants (unaffected feet and Hallux Valgus) completed the same experimental protocol. Participants walked forward at a comfortable pace, from one end of the lab to the other (approximately 10m), focusing their attention straight ahead. Prior to any experimental trials, participants were asked to practice walking along the walkway to determine their starting position, ensuring that consistent force plate contact and normal gait velocity was maintained for each trial. Participants were informed that a slip will be induced randomly during the walking trials. During each trial, a research assistant walked alongside the participant in case of a complete loss of balance. High friction floor coverings (sandpaper sheets) were secured at equal distances two steps before, on, and two steps after the force plates to ensure visual deception of the actual location of the slip mat (Figure 6). The unexpected slip was invoked by a slip mat consisting of wax paper adhered to the underside of a sandpaper sheet that was swapped in on the force plate to elicit an unexpected slip (Figure 7). Previous literature has reported the slip mat to have similar frictional properties to that of wet ice (wax paper friction = 0.10 ± 0.01; wet ice friction = 0.05-0.1) (Siegmund et al. 2006; Heiden et al. 2006). Between each trial, the participant was asked to face the back wall while the sandpaper sheet on the force plate was swapped or re-secured. Similar noises were made during this time to ensure the location of the slip mat and which trial would elicit a slip would remain unknown. Participants completed a block of at least five (n=5) straight walking trials, no slips. Following this block, the next block of five trials for each participant will have a randomly chosen trial where the first slip will occur. This is to ensure that participants have a regular gait pattern before a slip perturbation is presented. Then following this slip trial, a consecutive slip trial will occur, totaling two slip perturbations (n=2) within the first 10 trials of the protocol. The remaining ten walking trials (n=10) will contain one slip perturbation (at least 5 trials after the previous slip trial) and all others will be non-slip walking trials. This is a total of twenty (n=20) trials for the protocol (see Appendix B).

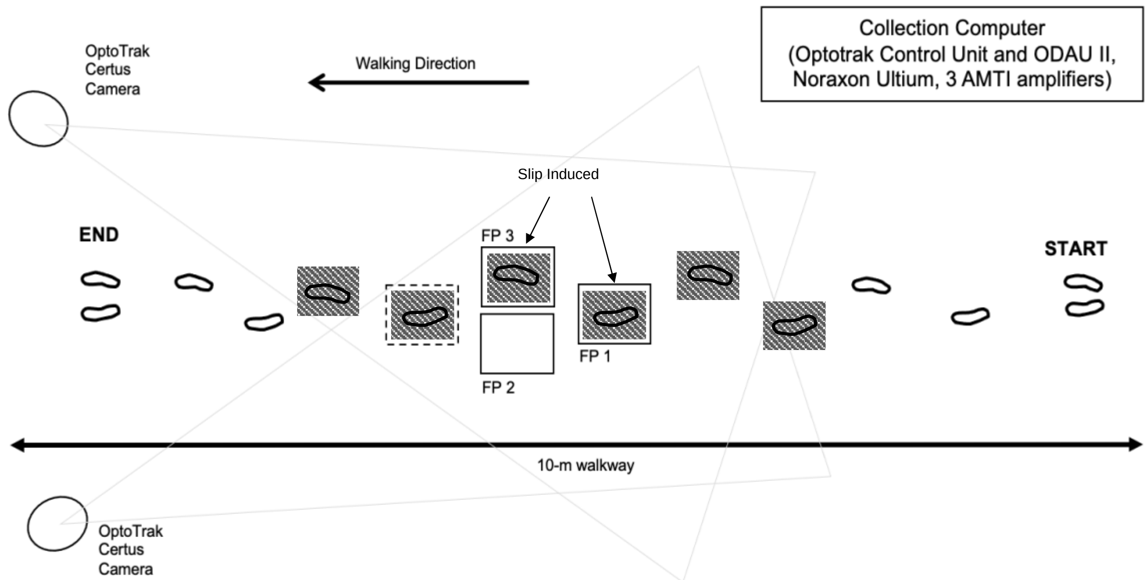


Figure 7: Diagram of the laboratory set-up: 10m walkway, force plates, OptoTrak cameras, and sandpaper mats.

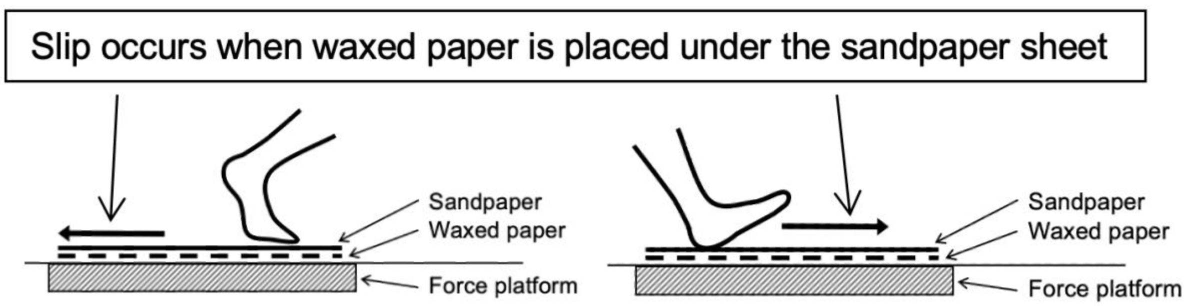


Figure 6: Diagram of the slip apparatus eliciting an anterior-posterior slip at toe off (left) or at heel contact (right) in the research laboratory.

3.3 Electromyography

Muscle activity was collected via fine-wire intramuscular and surface EMG at a sampling frequency of 1000Hz. Bipolar fine-wire intramuscular electrodes were used to record EMG signals from adductor hallucis-transverse, extensor hallucis brevis, flexor hallucis longus, and tibialis posterior in the perturbed/leading limb. The electrodes were constructed from 0.005mm copper coated wire (California Wire Company, Grover Beach, CA, USA) inserted into a 30mm length (27 gauge) single-use hypodermic needle (BD Precision Glide, Franklin Lakes, NJ, USA). Approximately 1mm of insulation was stripped from the end of the wire and bent around the tip of the needle to hook into the muscle when the needle was removed. A modified prefabricated 50mm length (25 gauge) single-use hypodermic needle (Rhythmlink, Columbia, SC, USA) was also used to insert into tibialis posterior as this muscle was typically at a depth past 30mm. During data collection, a band-pass filter (10-500Hz high-low cut off) was applied to the EMG signals. The raw EMG signals were unbiased and processed using full wave rectification with a 40Hz Butterworth dual pass low pass filter to linear envelope the signal in order to observe the onset of muscle activity of the reactive response. An amplitude threshold was identified during a quiet period (no muscle activity) for each muscle using the mean plus typically two standard deviations, with adjustments being made so that the amplitude thresholds have a minimum of 80% of quiet activity below. A temporal threshold was also identified to eliminate small bursts in the EMG signal that may exceed the amplitude threshold. Muscle activation that is above the amplitude threshold with a duration of >100ms was identified as muscle activation and this assisted in identifying muscle activity onset and cessation. Simultaneous force plate data measured (filtered with a low-pass dual-pass at 10Hz) at initial contact (>10N threshold) of the third force plate until toe off (<10N) permitted the determination of key gait cycle events to associate with timing of muscle activity during both normal gait and unexpected slip trials. Initial contact of the third force plate acted as a reference for the perturbed/leading limb during both normal gait and unexpected slip trials to identify changes in muscle activity timing when comparing normal gait trials to unexpected slip trials. The magnitude of muscle activity was assessed using the area under the EMG curve from the onset to cessation of muscle activity during initial contact of the perturbed/leading limb and collected during level walking and unexpected slip trials. Baseline muscle activity magnitude was collected when the participant was in quiet stance to determine activation (amplitude) threshold. Both fine-wire and surface EMG signals were normalized to the peak of an average EMG curve by obtaining the maximum EMG magnitude value during 0-100% of the stance phase over force plate 3 for each individual within their level walking and slip trial for each muscle and used as a reference point to determine muscle activation expressed as a percent of that value. Ensemble averages were also examined as a method to time normalize the signals. Ensemble averages were calculated using the linear enveloped signals for each participant and measured over force plate 3 from 0-100% of the stance phase.

3.4 Kinetic and Kinematic Variables

Ground reaction forces (GRF) were used to identify single stance during normal gait and slip perturbation trials from initial contact (>10N threshold) of the third force plate until toe off (<10N). GRF were also used as secondary measures to assist in quantifying slip severity and to support muscle activation results. The vertical force curve of the perturbed/leading limb was examined during the single stance phase of gait to observe changes in the maximum force as well as the duration of the contact phase. Anterior posterior shear forces of the perturbed/leading limb were also be examined during the single stance phase of gait. Specifically focusing on the maximum (or breaking force) as well as the duration of the breaking phase and the minimum (or maximum propulsive force) and the duration of the propulsive phase. Loading rate in the anterior posterior and vertical directions of the perturbed/leading limb were examined during initial contact and at toe off of the third force plate to assist in quantifying slip severity since these gait cycle events have been identified as having an increased probability of experiencing a slip. GRF were normalized to body weight (BW; kilograms*9.81m/s^2).

Kinematic data assisted in identifying segment and centre of mass (COM) position and velocity to quantify slip severity. COM was calculated using the kinematic markers to define a 7-segment model consisting of the head, trunk, pelvis, thighs, and shanks to perform a segmental COM calculation measured over the force plates (force plate 1 and 3) during a normal gait trial and compared to an unexpected slip. The toe and ankle marker displacement range and velocity maximum in the anterior-posterior direction were examined during single stance phase in the perturbed/leading limb. The toe and ankle markers were also used to calculate the absolute angle of the foot segment relative to the floor in the sagittal plane during single stance phase. Foot angle range and angular velocity was examined to assist in determining slip severity. COM velocity in the anterior-posterior and vertical directions were also evaluated to determine whole body disruptions to balance during a slip perturbation.

3.5 Statistical Analysis

All comparisons between non-slip and slip trials in participants with unaffected feet were analyzed using SAS Studio (SAS OnDemand for Academics). Between-subject effects (unaffected feet vs. Hallux Valgus) were not examined with an ANOVA due to unequal sample sizes, as this lack of statistical power could potentially result in a type II error. Outcome measures were evaluated using a within-subject, one-way repeated measures ANOVA, an average of five level walking trials compared to an average of three slip perturbation trials (non-slips vs. slips) with a significance level of $p<0.05$. Outliers above 3-4 standard deviations of the mean were investigated and removed if values were due to errors in collection (i.e., error in calculation during processing, noisy EMG signal, loss of signal, consideration of missing data code, etc.). A total of 5% of the EMG signals collected had to be removed due to errors in collection or type of slip perturbation. The Shapiro-Wilk test was used to assess normality of all outcome measures (muscle activity, kinematics, ground reaction forces). If $W<0.95$, then the ANOVA was performed with rank transformed data to achieve normalcy and the rank transformed p-value was reported.

4.0 Results

4.1 Slip Perturbation

During slip trials participants varied as to the severity of their perturbation as well as 'type' of slip. Type of slip was identified through visual inspection of video footage of each participants lower legs and feet. A total of fifty-six toe off slips (n=56) occurred, characterized by the slip mat sliding backwards at toe off. A total of two flat foot slips (n=2) occurred, characterized by a flat foot at initial contact and the participant gliding along the force plate on top of the slip mat. Lastly, a total of two heel contact slips (n=2) occurred, characterized by the slip mat sliding forwards at heel contact. Different types of slips (heel contact and flat foot) were removed from analysis. Analysis was isolated to the toe-slips (n=56) across muscle activity (onset, duration, and normalized magnitude), kinematics, and ground reaction forces (see Appendices E – J for tables reporting means, standard deviations and p-values for all outcome measures comparing non-slips to slips).

The average contact with force plate 3 (stance phase) during level walking (675.5ms ± 64.0) and slips (631.0ms ± 64.1, $p<0.0001$), where the stance phase during slips was reduced compared to level walking. In individuals with Hallux Valgus, the average contact with force plate 3 during level walking (630ms ± 59.0) and slips (614.8ms ± 47.0, $p=0.175$) was not significantly different.

4.2 Electromyography

Of the 20 completed intramuscular EMG insertions into each muscle: 18 successful signals were generated in the transverse head of adductor hallucis and tibialis posterior, 20 successful signals were generated in extensor hallucis brevis and flexor hallucis longus.

Participants reported minimal discomfort in all intramuscular EMG insertion locations during the experimental protocol however, if a specific insertion caused an altered gait pattern or there were anatomical limitations (i.e., calcification of the third and fourth metatarsal heads preventing insertion into the transverse head of adductor hallucis, or tibialis posterior located at a depth greater then 50mm), then the fine-wire electrodes were removed and collection proceeded without collecting activity from that specific muscle. If the signal from a specific muscle was noisy, those signals were disregarded, and an alternative trial was analyzed if possible. It is important to note that EMG artifacts were identified in one participant's right (perturbed/leading limb) peroneus longus, these signals were discarded from analysis. Additionally, in a singular case, the fine-wire electrodes recording activity from the transverse head of adductor hallucis broke mid-way through the experimental protocol. Muscle activity within trials prior to this issue were analyzed in this singular case.

A maximum of three bursts (temporal threshold of >100ms and an amplitude threshold with a minimum of 80% of quiet activity below) were identified within each muscle from 0% to 100% of the contact phase during non-slip and slip perturbation trials. Frequency of bursts (1st, 2nd, and 3rd bursts) were examined to identify differences in muscle activation patterns during level walking and slip perturbations (see Appendix D for frequency tables of muscle burst occurrences (1st, 2nd, and 3rd)). Measurement of multiple bursts during the stance (contact) phase allowed for direct comparison of the first burst of a muscle during level walking against the first bursts of the same muscle during a slip as this may inform us if a muscle is displaying more activation during reactive responses if the frequency of bursts increases (see Figure 8).

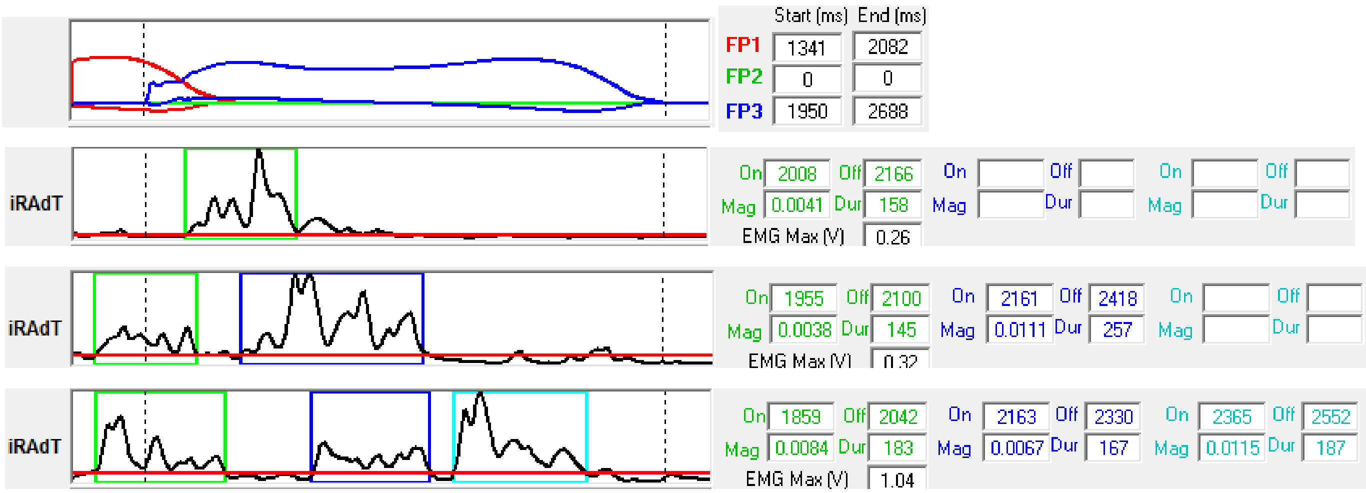


Figure 8: Example of how one to three muscle bursts in the linear-enveloped transverse head of adductor hallucis (iRAdT) EMG signal within a single participant were identified in the analysis program based on the amplitude (minimum of 80% quiet activity below the red line) and temporal (>100ms) thresholds. A first burst during the force plate contact phase (top panel) can be seen within a green box. A second burst during force plate contact phase can be seen within a dark blue box. A third burst during force plate contact phase can be seen within a light blue box. Force plate contact timing is identified by the two vertical dashed lines.

4.2.1 Perturbed/Leading Limb

During level walking trials, the average *onset* of the second burst of flexor hallucis longus was 336.3ms ± 159.2 after initial contact of force plate 3. Onset did significantly differ between level walking and slip perturbations (419.5ms ± 150.7, p=0.032), with flexor hallucis longus exhibiting a delayed onset during slip perturbations compared to level walking (see Figure 9a).

During level walking trials, the average *onset* of the first burst of tibialis posterior was 21.4ms ± 130.8 after initial contact of force plate 3. Onset did significantly differ between level walking and slip perturbations (78.4ms ± 189.3, p=0.012), with tibialis posterior exhibiting a significantly delayed onset during slip perturbations compared to level walking (see Figure 9b). The average *duration* of the third burst did significantly differ between level walking (181.9ms ± 114.5) and slip perturbations (207.4ms ± 122.3, p=0.010), as the tibialis posterior exhibited an increase in the duration of activation during slip perturbations compared to level walking (see Figure 9c).

During level walking trials the average *normalized magnitude* during the first burst in tibialis anterior did significantly differ between level walking and slip perturbations (5.6% ± 3.1 vs. 5.0% ± 2.8, p=0.005), as modulation of normalized muscle activity magnitude decreased in the tibialis anterior during slip perturbations compared to level walking. The average *normalized magnitude* during the second burst did significantly differ between level walking and slip perturbations (3.8% ± 2.0 vs. 4.6% ± 2.4, p=0.035), as modulation of normalized muscle activity magnitude increased in the tibialis anterior during slip perturbations compared to level walking.

During level walking trials, the average *duration* of the first burst in peroneus longus did significantly differ between level walking (291.7ms ± 117.7) and slip perturbations (251.5ms ± 81.7, p=0.005), as the peroneus longus displayed a decrease in the duration of activation during slip perturbations compared to level walking.

4.2.2 Non-Perturbed/Trailing Limb

During level walking trials, the average *onset* of the first burst of peroneus longus was prior to initial contact of the leading/perturbed limb on force plate 3 (-14.9 ± 156.1). Onset did significantly differ between level walking and slip perturbations (37.6ms ± 198.2, p=0.024), as peroneus longus exhibited a delayed onset during slip perturbations compared to level walking. The average *duration* of the first burst did significantly differ between level walking (172.0ms ± 111.4) and slip perturbations (196.5ms ± 104.2, p=0.046), as the peroneus longus displayed an increase in the duration of activation during slip perturbations compared to level walking. The average *onset* of the second burst of peroneus longus was after initial contact of the leading/perturbed limb on force plate 3 (349.8 ± 174.4). Onset did significantly differ between level walking and slip perturbations (412.0ms ± 161.7, p=0.041), as peroneus longus exhibited a delayed onset during slip perturbations compared to level walking.

During level walking trials, the average *normalized magnitude* during the third burst did significantly differ between level walking and slip perturbations (2.6% ± 2.3 vs. 6.2% ± 4.4, p<0.0001), as modulation of normalized muscle activity magnitude increased in the abductor hallucis of the non-perturbed/trailing limb during slip perturbations compared to level walking (see Figure 9d).

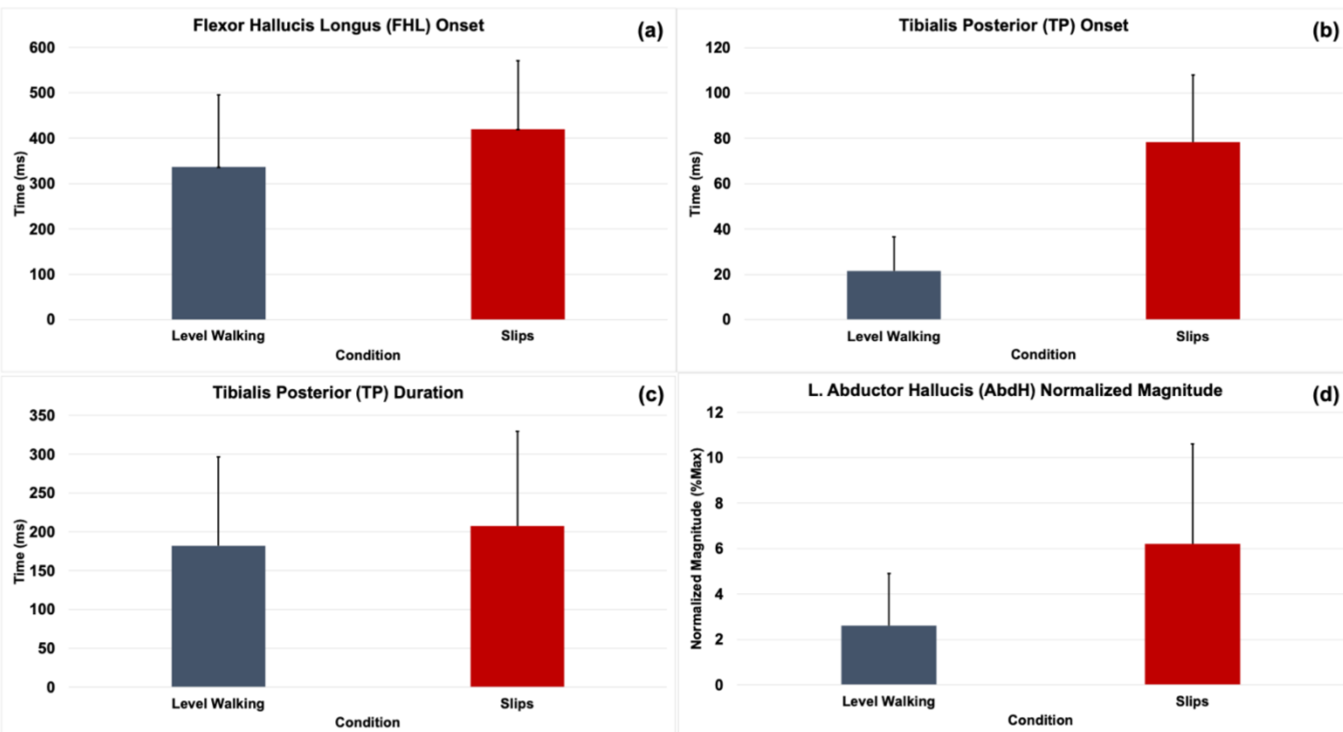


Figure 9: Muscle activity (onset, duration, and normalized magnitude) of the muscles within the deep lower leg and foot in unaffected feet displaying significant differences during slips (red) compared to level walking (blue).

4.2.3 Perturbed/Leading Limb – Hallux Valgus

During level walking trials, the average *duration* of the second burst of flexor hallucis longus did significantly differ between level walking (171.4ms ± 51.3) and slip perturbations (311.4ms ± 191.8, $p=0.006$), as the flexor hallucis longus displayed an increase in the duration of activation during slip perturbations compared to level walking (see Figure 10a).

During level walking trials, the average *normalized magnitude* of abductor hallucis during the first burst did significantly differ between level walking and slip perturbations (3.7% ± 3.3 vs. 6.2% ± 4.9, $p<0.009$), as modulation of normalized muscle activity magnitude increased during slip perturbations compared to level walking (see Figure 10b).

4.2.4 Non-Perturbed/Trailing Limb – Hallux Valgus

The average *duration* of the second burst of tibialis anterior did significantly differ between level walking (302.8ms ± 150.5) and slip perturbations (194ms ± 36, $p=0.015$), as tibialis anterior exhibited a decrease in the duration of activation during slip perturbations compared to level walking.

During level walking trials, average *duration* of the second burst of peroneus longus did significantly differ between level walking (227ms ± 77.4) and slip perturbations (168.4ms ± 61.1, $p=0.026$), as peroneus longus displayed a decrease in the duration of activation during slip perturbations compared to level walking.

During level walking trials, the average *duration* of the first burst of abductor hallucis did significantly differ between level walking (193ms ± 78.1) and slip perturbations (165.2ms ± 45.8, $p=0.012$), as abductor hallucis exhibited a decrease in the duration of activation during slip perturbations compared to level walking (see Figure 10c).

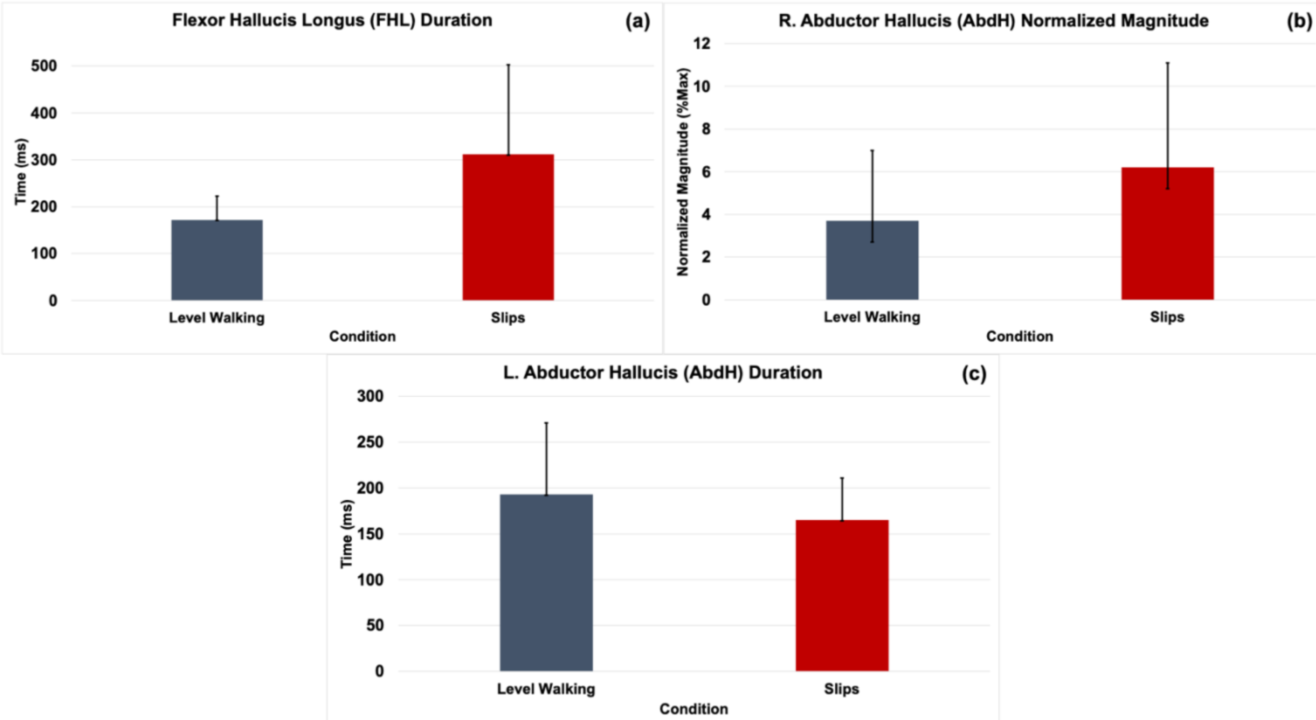


Figure 10: Muscle activity (onset, duration, and normalized magnitude) of the muscles within the deep lower leg and foot in those with Hallux Valgus displaying differences during slips (red) compared to level walking (blue).

<u>4.2.5 Ensemble Averages</u>

Ensemble averages were generated for five level walking trials for each muscle and each participant (unaffected feet and individuals with Hallux Valgus). A total of five muscles of interest (transverse head of adductor, extensor hallucis brevis, flexor hallucis longus, tibialis posterior, and abductor hallucis) from the leading or perturbed limb were examined further and graphed against slip 1, slip 2, and slip 3 for each participant. It is important to note that slips within a single participant could not be ensemble averaged as the slip perturbations experienced were highly variable. Additionally, because of this variability slip 1, slip 2, and slip 3 could not be examined as group effects (E.g., slip 1 ensemble average for the transverse head of adductor hallucis across all participants). A sample of ensemble average graphs displaying the muscle activation recorded from the transverse head of adductor hallucis, extensor hallucis brevis, flexor hallucis longus, and tibialis posterior via fine-wire intramuscular EMG within a single participant with unaffected feet and a single participant with Hallux Valgus can be seen in Appendix C to display the variability of activation during level walking and across all three slips (Appendix C). The following section reports ensemble averages of lower leg and intrinsic foot musculature as a group within the individuals with unaffected feet and those with Hallux Valgus.

Ensemble averages of 15 participants with unaffected feet revealed similar EMG activity of AddT. Biphasic activity was identified at 0-20% and 80-100% of the stance phase during level walking trials and a single burst was identified at initial contact (0-20%) of stance phase. Bursting patterns across slips (slip 1, 2, and 3) was highly variable across participants. An increase of EMG activity at 0-20% of the contact phase or the presence of a burst at 40-60% of the contact phase was observed during slips. Ensemble averages of 3 participants with Hallux Valgus revealed similar EMG activity of AddT. A single burst was identified at initial contact (0-20%) in the majority of participants and a single burst was identified at toe off (80-100%) of the stance phase during level walking. Bursting patterns across slips (slip 1, 2, and 3) was highly variable across participants. An increase of EMG activity at 0-20% of the contact phase during the slips or a burst around mid-stance (40-50% and 60-80%) was also observed during slips.

Ensemble averages of 16 participants with unaffected feet revealed variation within EMG activity of EHB. Bursting was either at initial contact (0-20% of stance) or at toe off (80-100% of stance) during level walking. Bursting patterns across slips (slip 1, 2, and 3) was highly variable across participants. An increase of bursting at initial contact and toe off was observed during slips. Some participants displayed minimal to no activation during both level walking and slip perturbations. However, some individuals that displayed no activation during level walking exhibited an increase of muscle activity at initial contact during slips. Ensemble averages of 4 participants with Hallux Valgus revealed variation within EMG activity of EHB. Bursting was at initial contact (0-20% of stance) and toe off (80-100% of stance) during level walking. Additionally, one participant exhibited a burst only at initial contact (0-10% of stance) and another participant displayed minimal activity during level walking. Bursting patterns across slips (slip 1, 2, and 3) was similar across participants with an increase of bursting at initial contact and/or toe off observed during slips.

Ensemble averages of 16 participants with unaffected feet revealed similar EMG activity of FHL. A burst at initial contact (0-20%) was observed across the majority of participants during level walking. Bursting patterns across slips (slip 1, 2, and 3) was similar across participants. Flexor hallucis longus exhibited three bursts at initial contact (0-20%), during mid stance (40-60%), and at heel contact (80-100%) during slips. Ensemble averages of 4 participants with Hallux Valgus revealed variation within EMG activity of flexor hallucis longus. Bursting was either at initial contact (0-20% of stance) or at toe off (80-100% of stance) during level walking. Bursting patterns across slips (slip 1, 2, and 3) was highly variable across participants. An increase of bursting at initial contact (0-30%) or toe off (80-100%) was observed during slips. Additional bursting during mid-stance (30-40%) was exhibited in a single participant.

Ensemble averages of 15 participants with unaffected feet revealed similar EMG activity of TP. A burst at initial contact (0-20%) was observed across the majority of participants. A long burst from initial contact to midstance (0-50% or 60%) was also observed during level walking. Bursting patterns across slips (slip 1, 2, and 3) was similar across participants. An increase of EMG activity at 0-20% of the contact phase was observed during the slips. The presence of a burst at 80-100% of the contact phase was also observed in some participants during slips.

Ensemble averages of 3 participants with Hallux Valgus revealed similar EMG activity of TP. Biphasic activity was identified at initial contact (0-20%) and mid stance (40-60%) during level walking. Bursting patterns across slips (slip 1, 2, and 3) was variable across participants. Consistent bursting throughout the stance phase was exhibited during slips. Additionally, an increase of EMG activity at 0-20% of the contact phase was exhibited in a single participant during the slips.

Ensemble averages of 16 participants with unaffected feet revealed similar EMG activity of AbdH. Bursting was either at initial contact (0-20% of stance) or at toe off (80-100% of stance) during level walking. Bursting patterns across slips (slip 1, 2, and 3) was highly variable across participants. The presence of a burst at toe off (80-100%) was observed. Additionally, an increase of activity throughout the stance phase was observed in some participants during the slips. Ensemble averages of 4 participants with Hallux Valgus revealed variation within EMG activity of AbdH. Bursting was exhibited during the latter half of stance (60-100%) during level walking. Consistent activity from 0-80% of stance was observed in a single participant while minimal activity was present from 0-100% of stance in a different participant during level walking. Bursting patterns across slips (slip 1, 2, and 3) was highly variable across participants. An increase of bursting at either initial contact (0-30% of stance) or at toe off (80-100% of stance) was observed during slips. Consistent activity from 0-80% of stance was also observed in a single participant during slips.

4.3 Kinematics

4.3.1 Ankle Position and Velocity

The average *maximum anterior-posterior ankle marker displacement* significantly differed between level walking (1.07m ± 0.05) and slip perturbations (0.99m ± 0.05, p<0.0001), maximum AP ankle marker displacement was decreased during slip perturbations compared to level walking. The average *anterior-posterior ankle displacement range* was significantly different between level walking (0.15m ± 0.02) and slip perturbations (0.084m ± 0.034, p<0.0001), AP ankle displacement range was decreased during slip perturbations compared to level walking.

The average *anterior-posterior ankle velocity maximum* did significantly differ between level walking (2.99m/s ± 0.37) and slip perturbations (1.71m/s ± 0.41, p<0.0001), maximum AP ankle velocity was decreased, and the foot was not able to move forward along the walkway as quickly during slip perturbations compared to level walking. The average *anterior-posterior ankle velocity minimum* did significantly differ between level walking (-0.01m/s ± 0.04) and slip perturbations (-0.47m/s ± 0.61, p=0.010) minimum AP ankle velocity was reduced (foot moving backwards) during slip perturbations compared to level walking. The average *anterior-posterior ankle velocity range* did significantly differ between level walking (2.99m/s ± 0.37) and slip perturbations (2.17m/s ± 0.65, p=0.0003), AP ankle velocity range was decreased during slip perturbations compared to level walking.

Hallux Valgus Sub-Group

The average *anterior-posterior ankle displacement range* did significantly differ between level walking (0.14m ± 0.01) and slip perturbations (0.09m ± 0.03, p=0.044), AP ankle displacement range was decreased during slip perturbations compared to level walking.

The average *maximum anterior-posterior ankle velocity* did significantly differ between level walking (3.02m/s ± 0.30) and slip perturbations (2.05m/s ± 0.65, p=0.021), maximum AP ankle velocity was decreased, and the foot was not able to move forward along the walkway as quickly during slip perturbations compared to level walking. The average *anterior-posterior ankle velocity range* did significantly differ between level walking (3.05m/s ± 0.34) and slip perturbations (2.35m/s ± 0.52, p=0.030), AP ankle velocity range was decreased during slip perturbations compared to level walking.

4.3.2 Ankle Angle and Angular Velocity

The average *ankle angle range* did significantly differ between level walking (71.05˚ ± 5.89) and slip perturbations (68.62˚ ± 6.12, p=0.004) ankle angle range was decreased during slip perturbations compared to level walking.

The average *ankle angular velocity range* did significantly differ between level walking (891.96˚/s ± 308.94) and slip perturbations (1419.35˚/s ± 691.52, p<0.0001) ankle angular velocity range was increased during slip perturbations compared to level walking.

4.3.3 Centre of Mass Velocity

The average *maximum COM AP velocity* did significantly differ between level walking (3.10m/s ± 8.51) and slip perturbations (3.44m/s ± 9.49, p=0.010), maximum COM velocity was increased during slip perturbations compared to level walking. The average *minimum COM AP velocity* did significantly differ from between level walking (1.05m/s ± 0.24) and slip perturbations (1.06m/s ± 0.26), minimum COM velocity was increased during slip perturbations compared to level walking. The average *COM AP velocity range* did significantly differ between level walking (2.05m/s ± 8.72) and slip perturbations (2.37m/s ± 9.72, $p<0.0001$), COM velocity range was increased during slip perturbations compared to level walking.

Hallux Valgus Sub-Group

The average *maximum COM AP velocity* did significantly differ between level walking (1.48m/s ± 0.09) and slip perturbations (1.42m/s ± 11, $p=0.016$) maximum COM velocity was decreased during slip perturbations compared to level walking.

4.4 Ground Reaction Forces

Ground reaction force outcome measures were examined from 0-100% of the stance phase and further divided the first half (0-50%) and the second half (51-100%) of the contact (or stance) phase each. Anterior posterior shear and vertical forces were analyzed by examining the first half of the stance phase and then the second half of the stance phase. Loading rate in the anterior posterior and vertical direction was analyzed by examining initial contact (0-20% of contact phase, right after initial foot contact) and toe off (80-100% of contact phase, prior to toe off).

4.4.1 Anterior-Posterior Shear Forces

The average *maximum AP shear force* during the second half of the stance (contact) phase did significantly differ between level walking (-0.05BW ± 0.07) and slip perturbations (-0.04BW ± 0.06, $p=0.002$), maximum shear force was reduced during slip perturbations compared to level walking. The average *minimum AP shear force* during the second half of the stance (contact) phase did significantly differ between level walking (-0.14BW ± 0.08) and slip perturbations (-0.11BW ± 0.07, $p<0.0001$), minimum shear force was reduced during slip perturbations compared to level walking. The average *AP shear range* during the second half of the stance (contact) phase did significantly differ between level walking (64.48BW ± 45.68) and slip perturbations (54.36BW ± 35.42, p<0.0001), shear force range was decreased during slip perturbations compared to level walking (see Figure 11).

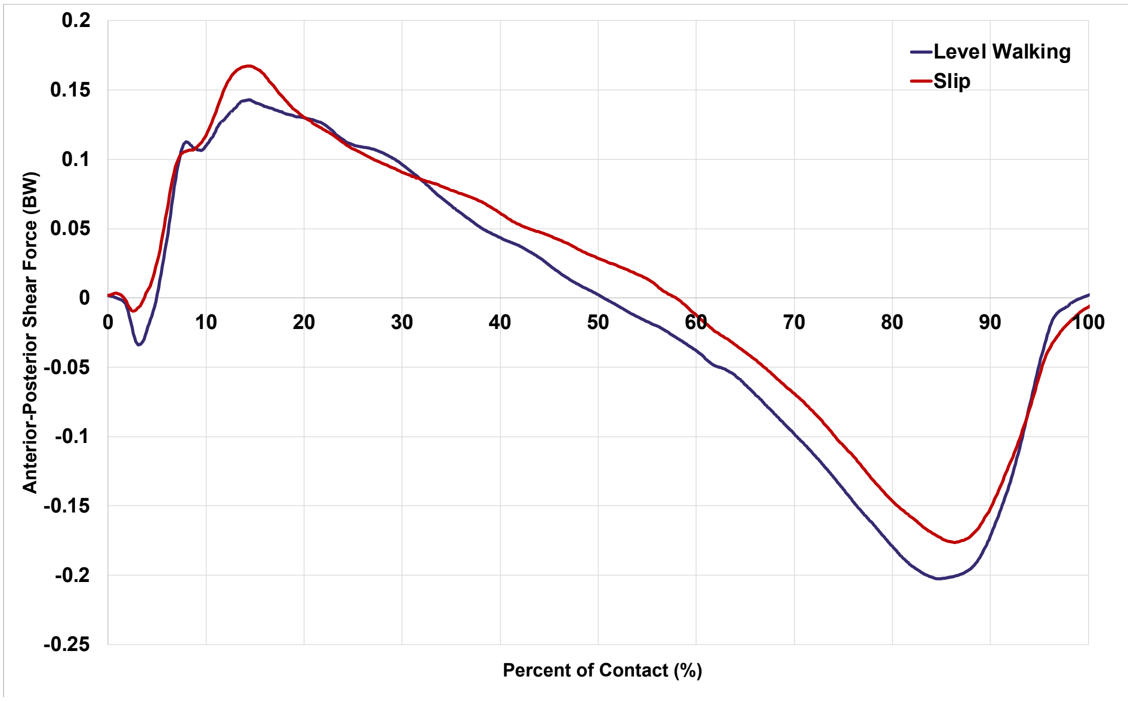


Figure 11: Anterior posterior shear force from a single participant comparing level walking (blue) to an unexpected slip (red), demonstrating the reduction in propulsive force during the second half of stance as a result of a toe off slip (+ breaking, – propulsive) .

<u>4.4.2 Vertical Forces</u>

The average *maximum vertical force* during the second half of the stance (contact) phase did significantly differ between level walking (0.95BW ± 0.21) and slip perturbations (0.99BW ± 0.15, p=0.028), maximum vertical force was increased during slip perturbations compared to level walking. The average *minimum vertical force* during the second half of the stance (contact) phase did significantly differ between level walking (0.67BW ± 0.36) and slip perturbations

(0.70BW ± 0.36, p=0.0003), minimum vertical force was increased during slip perturbations compared to level walking.

4.4.3 Loading Rate

Anterior-Posterior Loading Rate

The average *AP loading rate after initial contact* did significantly differ between level walking (1.21BW/s ± 1.26) and slip perturbations (1.32BW/s ± 0.98, p=0.0007) initial loading rate was increased during slip perturbations compared to level walking. The average *AP loading rate prior to toe off* did significantly differ between level walking (1.39BW/s ± 1.66) and slip perturbations (1.08BW/s ± 1.61, p<0.0001) loading rate at toe off was decreased during slip perturbations compared to level walking.

Vertical Loading Rate

The average *vertical loading rate after initial contact* did significantly differ between level walking (8.09BW/s ± 4.04) and slip perturbations (8.63BW/s ± 4.12, p=0.008), initial loading rate was increased during slip perturbations compared to level walking. The average *vertical loading rate prior to toe off* did significantly differ between level walking (-7.91BW/s ± 1.76) and slip perturbations (-8.62BW/s ± 5.70, p<0.0001), loading rate (unloading rate) at toe off was increased during slip perturbations compared to level walking.

5.0 Discussion

On average, muscle onset was delayed while an increase in duration and normalized magnitude was observed during slips compared to level walking in both individuals with unaffected feet and those with Hallux Valgus. Ankle marker position and velocity values decreased indicating backwards progression of the foot during slips compared to level walking. Changes in COM in the anterior-posterior direction indicated a disturbance to balance when experiencing a slip. A reduction in ankle angular velocity range indicated that during slips, full range of motion about the ankle was limited. This may be a result of increased contraction of lower leg muscles to increase stiffness as a proactive strategy to preserve balance. A reduction of propulsive force during the second half of the contact phase occurred during slips. Anterior-posterior and vertical loading rate differed after initial contact and prior to toe off during slips compared to level walking.

5.1 Muscle Activation during Non-Slip Trials

Muscle activation during level walking of the extrinsic foot muscles were similar to what has been previously reported (Hunt et al. 2001; Chambers and Cham 2007; Whittle et al. 2012; Zelik et al. 2015). Within the leading limb, the tibialis anterior exhibited an onset of activation prior to initial contact (-13.2% ± 3.3 of stance), eccentrically controlling plantarflexion and prior to propulsion (83.5% ± 16.4 of stance), to dorsiflex the foot for swing (Hunt et al. 2001; Murley et al. 2009b; Whittle et al. 2012; Zelik et al. 2015). Peroneus longus also displayed onset prior to initial contact (-13.9% ± 2.7 of stance), working in sync with the tibialis anterior to stabilize the ankle during early stance (Hunt et al. 2001). Flexor hallucis longus displayed onset of activation 1.7% ± 16.9 of stance, most likely to assist in stabilization of the ankle at initial contact (Knox et al. 2021). Tibialis posterior displayed onset of activity at initial contact (3.2% ± 20.0) and another onset of activation (57.3% ± 25.1) stabilizing the hindfoot in synergy with peroneus longus (67.9% ± 28.3 of stance) at mid-stance (Murley et al. 2009a).

Interestingly, the tibialis anterior displayed an onset of activation at mid-stance (68.4% ± 28.3 of stance; duration of 200.8ms), while the tibialis posterior displayed an onset of activity towards the end of stance (57.3% ± 25 of stance; duration of 181.9ms) during non-slip trials, which is not consistent in activation patterns previously reported within these muscles (Hunt et al. 2001; Murley et al. 2009a; Whittle et al. 2012). This may be a proactive strategy implemented as all participants were informed there would be a possibility of experiencing slips throughout the entire experimental protocol. Chambers & Cham (2007) explored muscle activity when anticipating slippery floors. It was revealed that when informing participants of the possibility of a slippery surface temporal activation of muscles differed. Co-contraction of ankle muscles within the stance leg were also observed (Chambers and Cham 2007). Differences in muscle activation patterns observed within the tibialis anterior at mid-stance and tibialis posterior at toe off may be a result of increased ankle stabilization and stiffness throughout stance to minimize the severity of a slip perturbation. In addition to this acting as a proactive strategy, this may also be present as a learning effect, following the first slip perturbation, which was typically a toe off slip. A burst of tibialis anterior muscle activity during mid-stance and a burst of tibialis posterior muscle activity towards the end of stance resulting in differences in ground reaction forces that may reduce the severity of a subsequent toe off slip perturbation.

Muscle activation during level walking of the intrinsic foot muscles were similar to what has been previously reported (Wong 2007; Zelik et al. 2015; Robb et al. 2021). Within the leading limb, the transverse head of adductor hallucis exhibited an onset of activation shortly after initial contact (5.9% ± 22 of stance) to stabilize the metatarsal heads as the foot makes contact with the ground and again around heel rise (second burst onset at 63.8 % ± 25.1 of stance and third burst onset at 67% ± 17 of stance; preparation for propulsion) to aid in forefoot stabilization for toe off (Robb et al. 2021). Extensor hallucis brevis exhibited two bursts of activation at the end of stance phase (74.5% ± 21.7 and 85.9% ± 9.2 of stance) to extend the first toe in preparation for toe off (Zelik et al. 2015). Onset of abductor hallucis was present towards the end of stance (73.1% ±17.4 of stance), supporting the medial longitudinal arch by assisting with proper force distribution at toe off (Reeser et al. 1983; Wong 2007).

Additional bursts within the intrinsic foot muscle group of the leading limb were observed during level walking trials within this study, revealing differing activation patterns compared to what has been previously reported. Extensor hallucis brevis exhibited onset of activity shortly after initial contact (15.5% ± 35.8 of stance), eccentrically controlling the hallux (first toe) at initial contact. Abductor hallucis also exhibited onset shortly after initial contact (12.7% ± 33.4 of stance) and during mid-stance (51.4% ± 20.7 of stance), dynamically supporting the medial longitudinal arch to potentially aid in foot stabilization as a proactive strategy to minimize the severity of a slip during the experimental protocol.

5.1.1 Unaffected Feet vs. Hallux Valgus

Visual comparison of muscle onset, duration, and normalized magnitude between those with unaffected feet and individuals with Hallux Valgus revealed speculative results that suggest the Hallux Valgus deformity may influence muscle function during the stance phase of gait. It is important to highlight that no statistical analyses were conducted to compare individuals with unaffected feet and those with Hallux Valgus during non-slip and slip trials. These findings must be interpreted with caution due to the lack of statistical evidence to support these claims as well as the extremely small sample size. Muscle onset of the leading limb differed within the transverse head of adductor hallucis, extensor hallucis brevis, and abductor hallucis. A delayed onset was observed in the transverse head of adductor in the Hallux Valgus group (67ms ± 191) compared to those with unaffected feet (38ms ± 144.2) following initial contact. A delayed onset was observed in extensor hallucis brevis in the Hallux Valgus group (159.2ms ± 275.3) compared to those with unaffected feet (106.9ms ± 244.1) following initial contact. A delayed onset was also observed in abductor hallucis in the Hallux Valgus group (116.9ms ± 247.6) compared to those with unaffected feet (80.4ms ± 217.9) following initial contact. Although, similar muscle duration and normalized magnitude was observed. Delay in muscle onset timing during stance may be a result of altered muscle mechanics within Hallux Valgus individuals. Previous studies have highlighted how Hallux Valgus can lead to structural changes, resulting in muscles adopting a new functional role. Extensor hallucis brevis becomes an adductor of the first toe while abductor hallucis loses its role in first toe abduction and becomes a flexor as it shifts to the plantar aspect of the foot (Alvarez et al. 1984; Arinci İncel et al. 2003; Stewart et al. 2013). These 'new' muscle functions may provide a preliminary explanation for the difference in muscle onset observed during the stance phase of gait in individuals with Hallux Valgus that warrants further investigation within future research.

Interestingly, differences in the tibialis posterior onset, duration, and normalized magnitude were observed. An earlier onset was observed in tibialis posterior in the Hallux Valgus group (-41.1ms ± 29.1 prior to initial contact) compared to those with unaffected feet (21.4ms ± 130.8 following initial contact). Duration and normalized magnitude increased in the Hallux Valgus group (270ms ± 110.2 and 6.3% ± 2) compared to those with unaffected feet

(192.5ms ± 80.8 and 4.1% ± 4.2). Previous literature has reported that the main role of tibialis posterior is to stabilize the hind foot and limit pronation (Murley et al. 2009a; Glasoe 2016). Additionally, individuals with Hallux Valgus have been reported to typically have a pes planus foot posture, in addition to excessive pronation of the foot (Atbaşı et al. 2020). Earlier onset of tibialis posterior may be an effort to maintain a more neutral ankle position prior to initial contact, counteracting pronation during the rest of stance. The observation of increased duration and normalized magnitude may also be a result of a pes planus foot posture associated with the Hallux Valgus deformity. Murley et al. (2009b) found that within individuals with flat-arched feet, the tibialis posterior appeared to be working harder, as a percent of maximum contraction, compared to those with normal arched feet. Similarities within individuals with Hallux Valgus and flat-arched feet may assist in explaining the difference in duration and normalized magnitude of tibialis posterior. The medial longitudinal arch may undergo greater loading in individuals with Hallux Valgus compared to unaffected feet, and an increase in loading may require increased magnitude and longer duration of activation to protect soft tissue structures from unnecessary stress and injury (Murley et al. 2009b). All other muscles in the perturbed/leading limb displayed similar onset, duration, and normalized magnitude following initial contact within both groups (unaffected feet, Hallux Valgus) during level walking trials.

5.2 Muscle Activation in Reaction to a Slip Perturbation

In response to the slip perturbations, findings did not support the first part of our first hypothesis that extrinsic foot muscles (TA, TP, and PL) would activate earlier with increased magnitudes. It was revealed that within the perturbed limb, the tibialis posterior exhibited a delayed onset. The peroneus longus in the perturbed limb displayed a reduction in duration of activity whereas the peroneus longus in the non-perturbed/trailing limb exhibited a delayed onset as well as an increase in the duration of activity during slip perturbations compared to level walking. Additionally, the tibialis anterior in the perturbed limb, had a reduction in the modulation of normalized muscle activity magnitude during slip perturbations compared to level walking. These differences observed during the first burst of the contact (stance) phase may be a result of the type of slip the majority of participants experienced. It was initially hypothesized that individuals would experience heel contact slip perturbations when in reality, most slips were experienced at toe off.

Analysis of the second burst during the contact phase revealed a delayed onset in flexor hallucis longus during the slip perturbation, supporting the first hypothesis that flexor hallucis longus would activate later with a diminished magnitude compared to level walking. Although normalized magnitude was not significantly different from level walking, differences in the onset of the second burst in flexor hallucis may be a result of the toe off slip perturbation. The role of flexor hallucis longus has yet to be explored within a slip perturbation context and its subsequent role during reactive balance control. During level walking, flexor hallucis longus has been reported to act as a dynamic ankle stabilizer of the rearfoot (Knox et al. 2021). Delayed onset of flexor hallucis longus observed in this study, may be due to the requirement of increased ankle stability during a toe off slip perturbation. The second burst of tibialis anterior had an increase in normalized muscle activity magnitude during slip perturbations compared to level walking. Tibialis anterior muscle activity has been examined during slip perturbations (Tang et al. 1998; Marigold and Patla 2002; Marigold et al. 2003; Heiden et al. 2006; Chambers and Cham 2007). Previous literature reported that in general, the tibialis anterior had an increase in power and duration during hazardous slips as this was likely to compensate for an ankle trajectory deviating from normal towards plantarflexion (Tang et al. 1998; Chambers and Cham 2007). Results from this study revealed within the tibialis anterior during a toe off slip there was a delayed onset and reduced magnitude at initial contact (first burst), followed by an increase of magnitude around mid-stance compared to level walking. A reduction of activity may have been a result of a flatter foot at initial contact as a more cautious gait pattern in an attempt to minimize the chance of experiencing a slip. Heiden et al. (2006) observed a reduction in activity at heel strike within the tibialis anterior and suggested that prior slip experience resulted in adopting a flatter foot angle. Results from this study also revealed increased normalized magnitude around mid-stance during slips. This may be due to the deviation of the ankle towards plantarflexion during a toe off slip, similar to findings reported by Tang et al. (1998). The second burst of peroneus longus in the non-perturbed/trailing limb exhibited a delayed onset during slip perturbations compared to level walking. Onset of this burst occurred at 64.7% of stance within the perturbed limb, which is during terminal stance of the perturbed limb prior to the non-perturbed/trailing limb making contact. The delayed onset exhibited within the peroneus longus of the non-perturbed/trailing limb may be a result of a postural adjustment as this muscle typically assists in ankle stabilization. Once the body initiates a reactive response and the body has recovered balance, the peroneus longus may exhibit onset to ensure balance is maintained as gait progresses.

Lastly, analysis of the third burst during the contact (stance) phase revealed an increase in the duration of tibialis posterior activity during slip perturbations compared to level walking. The role of tibialis posterior has not been explored in a slip context and its subsequent role during reactive balance control within previous literature. These findings suggest that the increase in the duration of tibialis posterior activity may be an attempt to stabilize the hindfoot and ankle as well as provide extra support of the medial longitudinal arch from potentially experiencing tissue stress during the toe off slip, as reported during level walking at mid-stance (Murley et al. 2009a, b). Findings did not support the second part of the first hypothesis that intrinsic muscles (transverse head of adductor hallucis, extensor hallucis brevis, and abductor hallucis) of the perturbed limb would exhibit earlier onsets and greater magnitudes in response to slip perturbations. Interestingly, modulation of muscle activity within abductor hallucis of the non-perturbed/trailing limb was increased during slip perturbations compared to level walking. This may be due to the slip perturbation occurring at toe off since the trialing limb has now become the supporting limb, the increase in muscle magnitude is likely due to abductor hallucis acting as a dynamic stabilizer during early stance to maintain balance during the slip (Reeser et al. 1983; Wong 2007).

5.2.1 Hallux Valgus

In response to slip perturbations, findings did support our second hypothesis that extrinsic and intrinsic foot muscles in the perturbed limb would exhibit greater magnitudes compared to level walking trials within Hallux Valgus individuals. Within the perturbed/leading limb, the abductor hallucis, an intrinsic foot muscle, exhibited an increase in the modulation of normalized muscle activity magnitude during slip perturbations compared to level walking. The increase in magnitude occurred at the beginning of mid-stance (27.6% of stance). The abductor hallucis has been reported to be an important muscle in the maintenance of the medial longitudinal arch during stance, as a decrease in muscular activity resulted in a decrease in arch height (Fiolkowski et al. 2003). An increase in normalized magnitude observed within this study may be an attempt to control for excessive foot pronation as well as provide additional support to the medial longitudinal arch when experiencing a toe off slip.

Analysis of the second burst during the contact phase revealed an increase in duration of flexor hallucis longus activity during slip perturbations compared to level walking. As reported previously, the flexor hallucis longus assists with ankle stabilization, as well as propulsion at the end of stance (Knox et al. 2021). An increase in the duration of flexor hallucis longus activity observed in this study, may be due to the need of increased ankle stability during a toe off slip perturbation. The abductor hallucis in the non-perturbed/trailing limb displayed a shorter duration of activation during slip perturbations compared to level walking. This may be due to muscle weakness within the intrinsic foot muscles associated in the Hallux Valgus deformity. Stewart et al. (2013) examined abductor hallucis muscle characteristics and found that dorso-plantar thickness and cross-sectional area decreased as Hallux Valgus severity progressed. Since muscle size is considered an important determinant of muscle strength these findings suggest a reduction in strength is a result of muscle disuse (Stewart et al. 2013). The shorter duration of muscle activity observed in the abductor hallucis reported within this study may be a result of inherent muscle weakness due to the Hallux Valgus deformity. The tibialis anterior and peroneus longus in the non-perturbed/trailing limb exhibited a shorter duration of activation during slip perturbations compared to level walking. Typically, these muscles work simultaneously to plantarflex the ankle and counteract inversion prior to making appropriate foot placement at initial contact (Hunt et al. 2001; Zelik et al. 2015). A shorter duration of muscle activity observed in both the tibialis anterior and peroneus longus suggests an interruption in the execution of proper foot placement for initial contact of the non-perturbed/trailing limb, since the reactive balance response may require a stepping response to maintain forward progression of gait.

Due to the sample size of individuals with unaffected feet (n=16) and those with Hallux Valgus (n=4), there was insufficient data to statistically examine between group differences (comparison of unaffected feet to those with Hallux Valgus) across both conditions (non-slips vs. slips). Thus, results did not support the first part of our second hypothesis, that muscle activity within the intrinsic and extrinsic muscle groups of individuals with Hallux Valgus would exhibit diminished magnitudes compared to those with unaffected feet during slips. However, visual inspection of EMG ensemble averages may provide preliminary differences in bursting patterns from 0-100% of the contact (stance) phase during slips between unaffected feet and the Hallux Valgus sub-group.

5.2 Kinematics

In response to slip perturbations, findings did not support our third hypothesis that reactive balance control will be diminished in individuals with Hallux Valgus compared to those with unaffected feet. Between group (unaffected feet vs. Hallux Valgus) differences across both conditions (non-slips vs. slips) were not examined due to insufficient sample size. However, significant differences in maximum COM velocity and COM velocity range in the anterior-posterior direction were observed, indicating changes in balance occurred in individuals with unaffected feet when experiencing slips. Maximum COM velocity and minimum COM velocity in the anterior-posterior direction increased during slip perturbations compared to level walking. Additionally, COM velocity range in the anterior-posterior direction increased during slip perturbations compared to level walking. This finding suggests that the COM experiences a sudden increase in velocity forward along the walkway (positive anterior-posterior direction) during mid-stance to toe off during a toe off slip, compared to a consistent COM AP velocity trajectory during the transition from mid-stance to toe off experienced during level walking.

Analysis of ankle marker position and velocity in the anterior posterior direction as well as ankle angle and ankle angular velocity in the sagittal plane revealed interesting differences about the characteristics of slips experienced. Maximum ankle marker position and ankle marker position range in the anterior-posterior direction decreased during slips compared to level walking. Maximum and minimum ankle marker velocity in the anterior-posterior direction decreased during slips compared to level walking. Ankle marker velocity range in the anterior-posterior direction also significantly decreased during slips compared to level walking. Slip perturbations occurring at toe off have yet to be explored within the current literature focused on slips during gait, so these findings may further our understanding of different types of slips that can be experienced. During the contact (stance) phase when experiencing slips, a reduction in AP velocity (maximum and minimum values) may indicate a deviation from normal foot trajectory as the foot slides slightly backwards during a toe off slip. The reduction in AP marker velocity range supports this theory as the perturbed limb is not following its typical forward progression in space, resulting in a reduction of range.

Minimum ankle angle increased indicating more plantarflexion during slips compared to level walking. This finding may be a result of the toe off slip perturbation as the slip mat slid backwards, the ankle exhibited more plantarflexion at propulsion compared level walking. Ankle angle range decreased during slips compared to level walking. This reduction in ankle angle range indicates that the ankle was not able to move through the full range of typical plantarflexion/dorsiflexion during slips. Maximum ankle angular velocity and ankle angular velocity range increased during slips compared to level walking. Minimum ankle angular velocity decreased during slips compared to level walking. The largest angular velocity at the ankle joint has been reported to occur during the push-off phase in level walking, as the ankle plantarflexes (Mentiplay et al. 2018). The increase in maximum angular velocity as well as angular velocity range observed within this study is likely a result of the toe off slip. The loss of friction at propulsion due to the toe off slip is leading to a more rapid plantarflexion moment at the ankle.

Hallux Valgus Sub-Group

Analysis of kinematic variables within individuals with Hallux Valgus revealed a decrease in maximum COM velocity in the anterior-posterior direction during slips compared to level walking. This finding suggests that the COM experiences a disruption to the forward (positive AP) COM momentum during the contact phase of a toe off slip, as a reduction in propulsive force may create an unstable situation, in comparison to consistent COM AP velocity trajectory experienced during level walking. Ankle marker position range in the anterior-posterior direction decreased during slips compared to level walking. Additionally, maximum ankle marker velocity and range in the anterior posterior direction decreased during slips compared to level walking. Similar findings in ankle marker position and velocity in the anterior-posterior direction were found in individuals with unaffected feet. During the contact (stance) phase when experiencing slips, a reduction in maximum AP velocity and range may indicate a deviation from normal foot trajectory as the foot slides slightly backwards during a toe off slip and does not follow the typical forward progression as observed during level walking. Similarities in ankle marker position and velocity between those with unaffected feet and individuals with Hallux Valgus when experiencing a slip may indicate that reaction to a toe off slip is similar regardless of structural differences in the foot. No significant differences in ankle angle or ankle angular velocity were observed in individuals with Hallux Valgus during slips compared to level walking.

5.3 Ground Reaction Forces

Analysis of anterior-posterior shear forces, vertical forces, and loading rate at different intervals throughout the contact (stance) phase also revealed interesting differences about the characteristics of slips experienced. A reduction in maximum and minimum anterior-posterior shear forces during the second half of the contact phase (51-100% of contact) was observed during slips compared to level walking. Additionally, anterior-posterior shear force range was decreased during slips compared to level walking. These results suggest there was a decrease in propulsive force due to a reduction of friction caused by the slip experienced at toe off. It was revealed that anterior-posterior loading rate after initial contact (0-20% of contact) increased whereas, prior to toe off (80-100% of contact), it decreased during slips compared to level walking. Previous literature has indicated that high loading rates increase the likelihood of experiencing a slip perturbation (Cham and Redfern 2002). Interestingly, increased AP loading rate following initial contact was observed within this study, but did not elicit a heel contact slip perturbation, as expected based on previous findings (Redfern et al. 2001; Cham and Redfern 2002). Detection of slip mat movement may have resulted in more of a flat foot contact, leading to a greater AP loading rate at initial contact, to potentially reduce the severity of a slip. A reduction in AP loading rate prior to toe off, supports findings mentioned previously in which a toe off slip decreases propulsive force due to the reduction of friction experienced.

Maximum and minimum vertical force during the second half of the contact phase (51-100% of stance) increased during slips compared to level walking. These findings suggest that more force must be produced to continue to propel the body forward during a toe off slip in order to maintain balance and a continuous gait trajectory. An increase of vertical loading rate after initial contact (0-20% of stance) was observed whereas prior to toe off (80-100% of stance), unloading rate increased during slips compared to level walking. The increase in vertical loading rate observed after initial contact may also be a result of a flatter foot angle at initial contact, as mentioned previously with AP loading rate following initial contact. An increase in vertical unloading rate was likely a result of experiencing a slip at toe off as the reduction in friction requires a quick shift of weight from the perturbed limb onto the non-perturbed/trailing limb to recover balance. No significant differences in ground reaction forces were observed during the different intervals of the contact (stance) phase in individuals with Hallux Valgus during slips compared to level walking.

6.0 Conclusion

6.1 Limitations

Prior to participation in this experimental protocol, all participants were informed (during recruitment and within informed consent) that the aim of this study was to examine slip perturbations during gait. Participants were aware that they would experience at least one slip perturbation during the experimental protocol. Prior knowledge that participants may experience a slip could have affected normal gait characteristics during the level walking trials. This could have also led to participants implementing proactive strategies such as shorter stride length or co-activation of muscles to preserve balance throughout the protocol. Participants were encouraged to walk as they typically would in everyday life and attempt to maintain a consistent gait velocity that was similar to practice trials. Ground reaction forces during level walking trials, such as vertical (8.09BW/s ± 4.04; unaffected feet, 7.81BW/s ± 4.76; Hallux Valgus) loading rate after initial contact, was similar to what has been previously reported (Marigold and Patla 2002; Marigold et al. 2003). Each participant experienced at least one slip perturbation during the experimental protocol therefore, it can be assumed that prior knowledge did not negatively influence data collection or the results and that our findings are representative of true changes in muscle activity during unexpected slips.

Previous slip perturbation literature examined slips occurring at heel/initial contact exclusively. This may be a result of differences within the methodology of how unexpected slips were elicited as it has been reported that slips have been elicited using contaminants (E.g., oil, soap/glycerol and water mixture) (Brady et al. 2000; Cham and Redfern 2001; Lockhart et al. 2003, 2005; Moyer et al. 2006, 2009; Chambers and Cham 2007; Beschorner and Cham 2008; Lockhart 2013; O’Connell et al. 2016), a set of rollers that could be locked or unlocked

(Marigold and Patla 2002; Marigold et al. 2003), force platform translations (Tang et al. 1998; Tang and Woollacott 1998), or changing the frictional properties of the shoe-floor interface (E.g. placing sheets of paper, waxed paper secured under sandpaper, aluminum foil along the walkway) (Siegmund et al. 2006; Heiden et al. 2006). Individual gait characteristics such as, gait velocity, step length, and shear force at initial contact influence the probability and severity of the slip experienced (Redfern et al. 2001; Moyer et al. 2006). Each of these different ways to elicit an unexpected slip may change gait characteristics, possibly influencing the type of slip experienced. Our method of eliciting a slip using waxed paper adhered to the underside of a sandpaper mat, allowed for foot displacement that would mimic the natural movement of a 'real world' slip. Undisclosed sequential order of level walking and slip trials, as well as visual and auditory deception of the slip mat, was utilized in an effort to make all slips unexpected. Additionally, participants were instructed to walk as they typically would at a self-selected gait velocity. This was with the intention of mimicking gait behaviour in the real world and thus, examining a natural unexpected slip. Examining toe off slips has real-world implications as the type of slip experienced can occur at initial contact or toe off depending on gait characteristics as well as the external environment.

Lastly, sample size of both the unaffected feet and individuals with Hallux Valgus groups was a limitation within this study. A sufficient number of participants was planned to be collected for both individuals with unaffected feet and those with Hallux Valgus. However, there was difficulty recruiting participants that had a mild to moderate Hallux Valgus deformity resulting in unequal groups, so between subject differences (unaffected feet vs. Hallux Valgus) during slips could not be examined. Additionally, the use of fine-wire intramuscular EMG within this study protocol provided a challenge with recruitment. Although sample sizes for both groups were small, significant results were still found and must be interpreted with caution, particularly within the Hallux Valgus group. In order to minimize the risk of a type I error, the significance level for all outcome measures was set at an appropriate value of 0.05. Findings within this study may provide foundational evidence for further exploration of lower leg and foot musculature during slips, as well as examining differences withing foot disorders, discussed in more depth within the next section.

6.2 Future Direction

This study revealed preliminary evidence that the muscles within the lower leg and foot are important for reactive balance control when recovering from a toe off slip perturbation. Replicating these results, specifically collecting fine-wire intramuscular EMG from the same muscles within a larger sample, will strengthen and confirm these findings. Furthermore, examining bilateral activity within the transverse head of adductor, extensor hallucis brevis, flexor hallucis longus, and tibialis posterior during slips may provide more insight on the role each of these muscles contribute to reactive balance control.

Further comparison of muscle onset, duration, and normalized magnitude during different gait cycle events (loading phase, mid stance, and propulsive phase) may provide a more thorough understanding of extrinsic (I.e., peroneus longus, flexor hallucis longus, tibialis posterior) and intrinsic foot muscles during both level walking and slips. This may also provide insight on the activation patterns of the extrinsic and intrinsic foot muscles to further our understanding of possible co-contraction or muscle synergy within the two groups during gait.

Examining type of slip (heel contact, flat foot, and toe off slip) changes to muscle activation patterns within extrinsic and intrinsic foot muscles would strengthen current findings and provide the opportunity for further hypotheses focused on exploring reactive balance strategies. Additionally, making comparisons between the influence of different types of slips on balance may provide additional insight into existing fall prevention strategies.

Investigation of a learning effect when exposed to multiple slips could provide insight into the comparison of extrinsic and intrinsic foot muscle activation during reactive and proactive strategies. Results from this current study examined muscle timing (onset and duration) and normalized magnitude across an average of slips 1, 2, and 3 compared to level walking. However, slips within participants are highly variable and would be best examined individually. When examining slip perturbations, the first slip should be treated as a true unexpected slip while a learning effect should be investigated within in all subsequent slips. Additionally, future studies should include a block of known level walking trials where participants are aware that no slip perturbations will be experienced. This will provide baseline gait characteristics that can be compared to level walking trials when the possibility of experiencing a slip is present.

Finally, a true comparison of extrinsic and intrinsic foot muscular activity within unaffected feet and those with Hallux Valgus during both level walking and slips would provide strength for the early evidence of differences in muscle mechanics and function during the stance phase reported in this study. Furthermore, collecting a larger sample of individuals with Hallux Valgus would further our current understanding of muscle timing and magnitude in the presence of a foot deformity during gait and may aid in the development of an orthotic intervention to improve balance and quality of life.

6.3 Concluding Statements

Extrinsic foot muscle timing and normalized magnitude in individuals with unaffected feet, were found to differ during slips to provide additional stability. In the perturbed/leading limb, superficial muscles such as the tibialis anterior and peroneus longus exhibited changes in onset and magnitude as a proactive strategy to reduce foot angle at initial contact and increase stiffness in the lower leg to minimize the severity of a slip. This was confirmed by an increase in both the anterior-posterior shear and vertical loading rate after initial contact. Deeper lower leg musculature, such as the flexor hallucis longus and tibialis posterior also displayed changes in onset and duration to provide additional stability of the hindfoot. These changes in muscle activation provided extra ankle stability that was required during a toe off slip to optimize foot position for a continuous progression gait.

Within the non-perturbed/trailing limb of individuals with unaffected feet, the abductor hallucis, an intrinsic foot muscle, displayed an increase of activity when it took on the role of the supporting limb during the toe off slip, demonstrating its role as a dynamic stabilizer of the foot. Additionally, changes in muscle activity observed in the tibialis anterior and peroneus longus of the non-perturbed/trailing limb support these findings, with the newly supporting limb assisting in maintenance of postural stability following a toe off slip.

Muscle activity within Hallux Valgus individuals displayed preliminary differences from those with unaffected feet during both level walking and slips. Tibialis anterior, peroneus longus, and abductor hallucis, in the non-perturbed/trailing limb, all displayed a shorter duration of activation during a slip. This may be an indication of muscle weakness in both the extrinsic and intrinsic foot muscle group. In the perturbed/leading limb, flexor hallucis longus and abductor hallucis exhibited an increase in muscle activity during slips. Interestingly, preliminary comparisons (slip trials in unaffected feet vs. slip trials in individuals with Hallux Valgus to compare reactive responses) within the flexor hallucis longus and abductor hallucis in individuals with Hallux Valgus revealed increased duration within the flexor hallucis longus and increased normalized magnitude, within the abductor hallucis compared to those with unaffected feet. Additionally, preliminary differences observed in the non-perturbed/trailing limb musculature (TA, PL, AbdH) revealed a shorter duration of activation compared to those with unaffected feet. This provides early evidence that muscles within Hallux Valgus individuals need to work harder to maintain balance control, because of structural differences. Future studies must collect a larger sample size of individuals with unaffected feet and those with Hallux Valgus to statistically compare muscle activity (timing and magnitude) during level walking as well as unexpected slips. The centre of mass velocity in the anterior-posterior direction in Hallux Valgus individuals demonstrated an unstable weight transfer during slips, supporting the preliminary differences observed in muscle activity mentioned above, as well as the theory that the Hallux Valgus deformity results in poor balance.

Findings from this study provide support that lower leg and foot musculature are important in maintaining balance following a toe off slip perturbation. Preliminary findings also provide rationale to further examine and compare the muscular activation patterns within the lower leg and foot muscles during gait in individuals with Hallux Valgus as differences in muscle timing and magnitude may be observed as a result from structural changes in the foot. This future work may support previous reports that the Hallux Valgus deformity influences muscle mechanics, thus dynamic balance.

Appendix A – Screening Questionnaire delivered electronically to all prospective participants via Qualtrics

Screening Questionnaire

Start of Block: Default Question Block

Q1 Name

____

Q2 Telephone Number

____

Q3 Email

____

Q5 Preferred method of communication

○ Email (1)

○ Telephone (2)

Q6 What is your age (years)?

____

Q7 What is your height (cm)?

____

Q8 What is your weight (kg)?

____

Q9 What is your shoe size?

____

Q10 What is your gender?

____

Q11 Do you use an assistive device for mobility purposes?

- ○ Yes (1)
- ○ No (2)

Q12 Can you walk 10m without the assistive device?

- ○ Yes (1)
- ○ No (2)

Q13 Do you have any conditions that limit the use of your arms or legs?

- ○ Yes (1)
- ○ No (2)

Q14 Do you have or have you ever had any of the following (Select all that apply):

- ▢ Paralysis (1)
- ▢ Epilepsy (2)
- ▢ Cerebral Palsy (3)
- ▢ Multiple Sclerosis (4)
- ▢ Parkinson's Disease (5)
- ▢ Stroke (6)
- ▢ Any other neurological disorder (7)
- ▢ Diabetes (8)
- ▢ Problem with your vision that isn't corrected with glasses (9)
- ▢ Cataract Surgery (10)
- ▢ A balance or coordination problem (11)
- ▢ An inner ear disorder (12)
- ▢ Hearing problems (13)
- ▢ Constant ringing in your ears (14)
- ▢ Ear surgery (15)

Q15 Do you have or have you ever had any of the following (Select all that apply):

- ☐ Problems with your heart or lungs (1)
- ☐ High blood pressure (2)
- ☐ Blood circulation problems (generally) (3)
- ☐ Blood circulation problems (specifically lower extremities) (4)
- ☐ Cancer (5)
- ☐ Arthritis (6)
- ☐ Rheumatism (7)
- ☐ Back problems (8)
- ☐ A joint disorder (9)
- ☐ A muscle disorder (10)
- ☐ A bone disorder (11)

Q16 Based on your response to the previous question, if you have selected 'yes' please explain (How much does the condition interfere with your activities?):

____

Q17 Have you ever severely injured or had surgery on your:

- [ ] Head (1)
- [ ] Neck (2)
- [ ] Back (3)
- [ ] Pelvis (4)
- [ ] Ankle, knee, or hip joints? (5)

Q18 Have you ever broken any bones? If 'yes' which ones?

____

Q19 Have you had any recent illnesses, injuries, and/or operations? If 'yes' please specify:

____

Q20 Do you have difficulties performing any daily activities? If 'yes,' which activities?

____

Q21 Please indicate if you are taking any medications such as tranquilizers, sedatives, and/or antidepressants (if 'yes,' you may be excluded from participating as these types of medications can affect balance control):

○ Yes (1)

○ No (2)

Q22 Do you currently wear foot orthotics? If 'yes' for what reason and how long have you been wearing these orthotics?

____

Q23 Manchester Scale bunion severity assessment sent via Email (Please select N/A if you DO NOT have bunions)

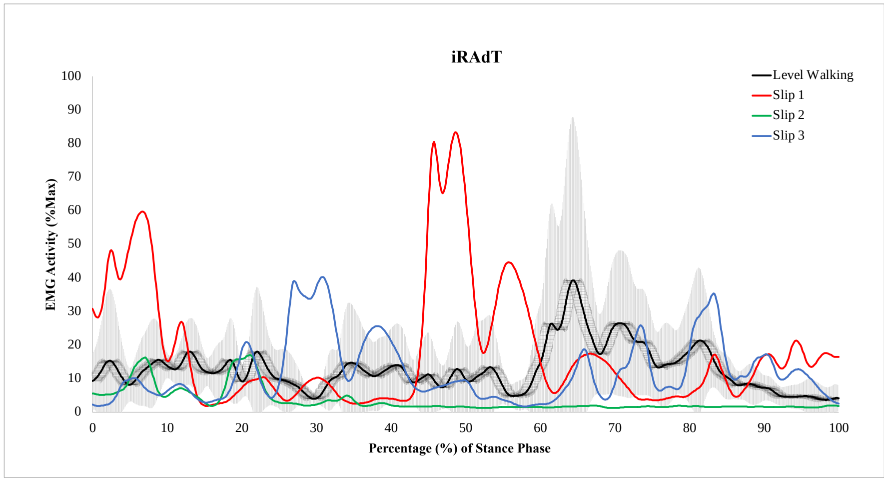
- ○ Photo A (1)
- ○ Photo B (2)
- ○ Photo C (3)
- ○ Photo D (4)
- ○ N/A (5)

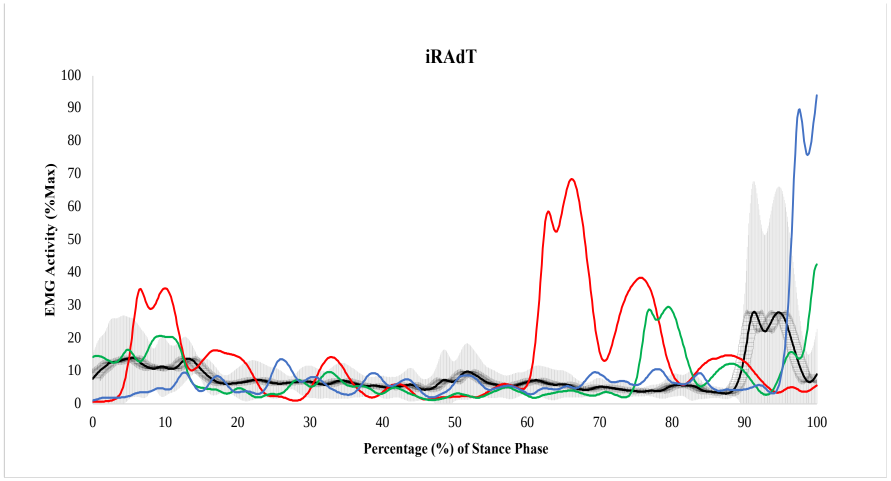
End of Block: Default Question Block

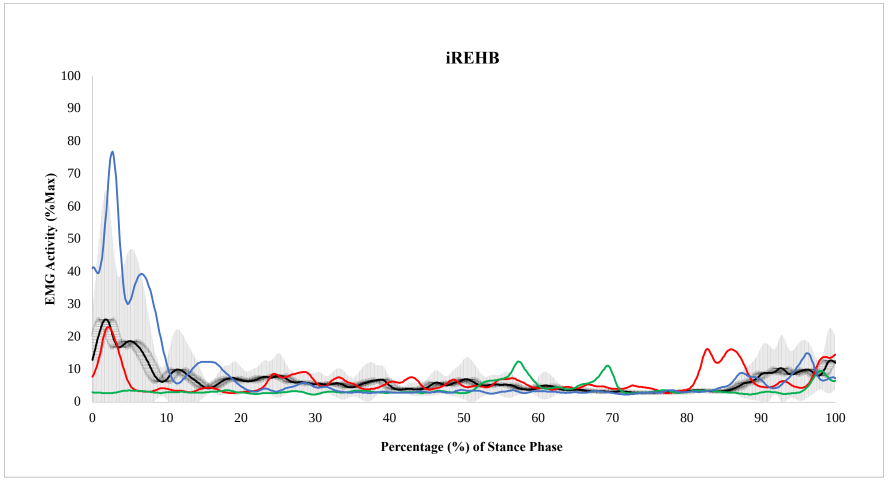
Appendix B – Sample experimental protocol consisting of a mixture of normal gait trials (n=17) and unexpected slip perturbations (n=3), with the first slip occurring at trial 6

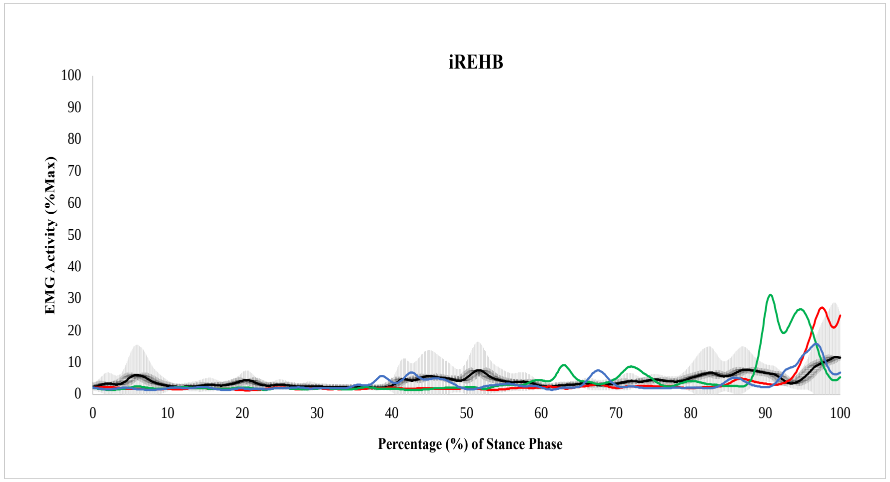
	Trial #	Slip Y/N	Comments
Quiet Standing	N/A	N/A	
Straight Walking Trials	1		
	2		
	3		
	4		
	5		
Slip Trials	6		
	7		
Straight Walking Trials	8		
	9		
	10		
	11		
	12		
	13		
Slip Trial	14		
Straight Walking Trials	15		
	16		
	17		
	18		
	19		
	20		

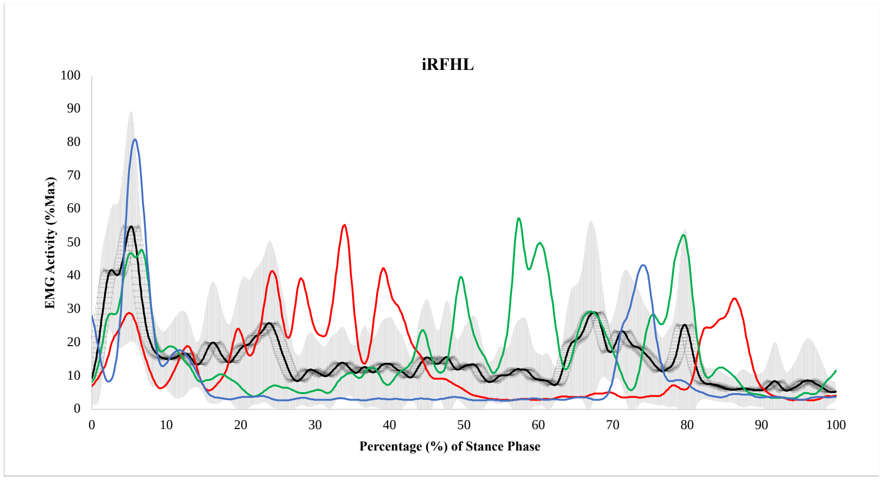
Appendix C – Ensemble average graphs displaying the variability of muscle activity during level walking (black; SD shown in grey) as well as slip 1 (red), 2 (green), and 3 (blue) in a single individual with unaffected feet (left) and a single individual with Hallux Valgus (right)







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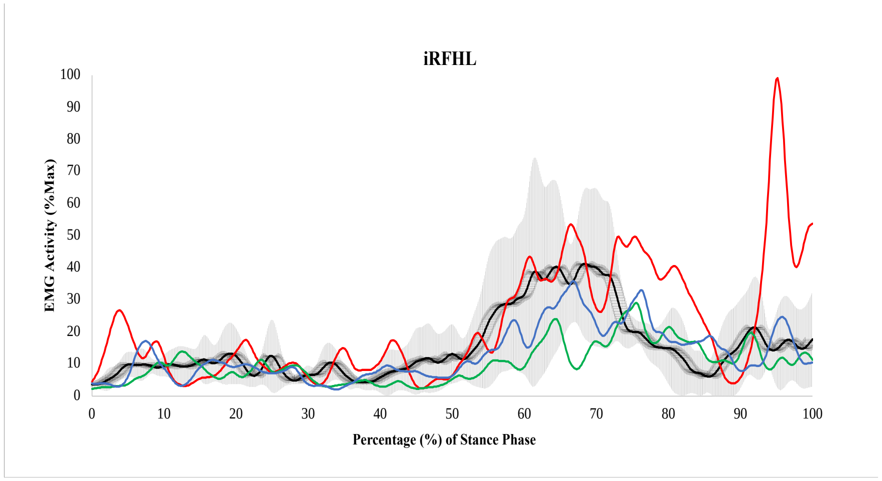
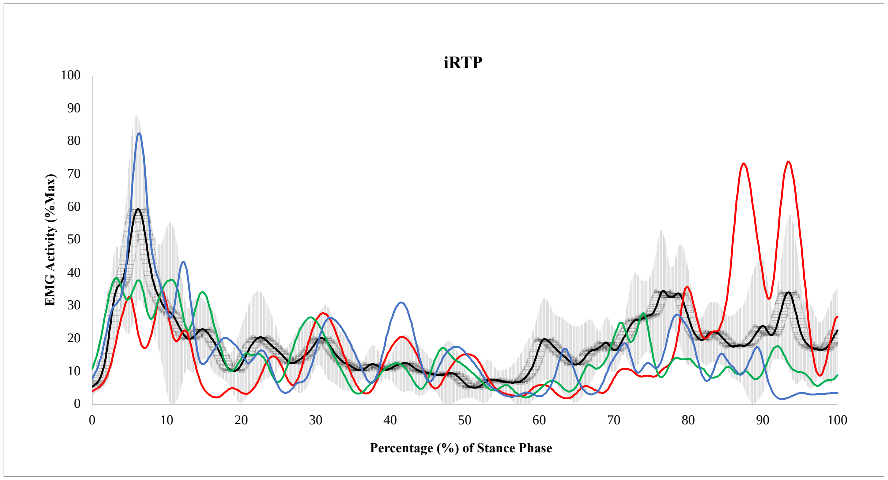
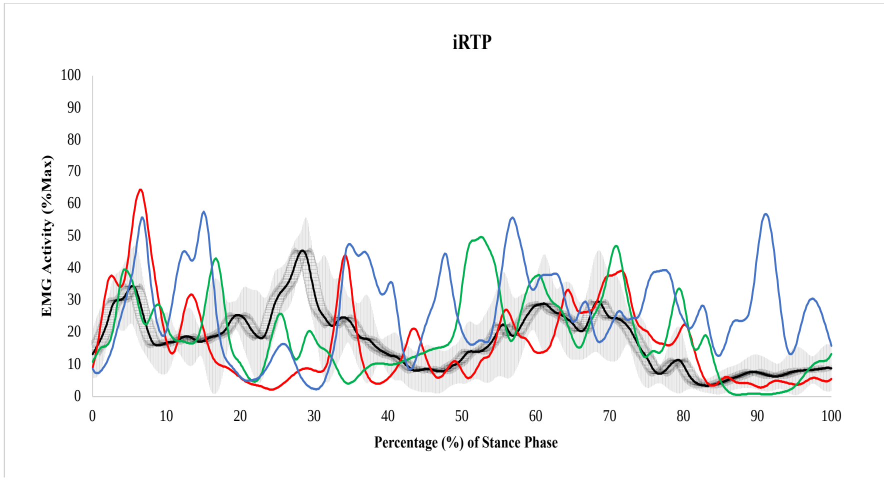
EMG Activity (%Max)
Percentage (%) of Stance Phase


iRFHL
EMG Activity (%Max)
Percentage (%) of Stance Phase


iRTP
EMG Activity (%Max)
Percentage (%) of Stance Phase


iRTP
EMG Activity (%Max)
Percentage (%) of Stance Phase

Appendix D – Frequency table of bursts within each muscle during non-slip and slip trials across participants with unaffected feet (n=16; top). (A maximum of 80 bursts during level walking (n=80) and a maximum of 44 bursts during slips (n=44) across all conditions and bursts; expressed as a percentage) and those with Hallux Valgus (n=4; bottom). (A maximum of 20 bursts during level walking (n=20) and a maximum of 12 bursts during slips (n=12) across all conditions and bursts; expressed as a percentage)

	First Burst		Second Burst		Third Burst	
	Level Walking	Slips	Level Walking	Slips	Level Walking	Slips
R. AddT	92.5%	86.4%	62.5%	65.9%	15%	15.9%
R. EHB	98.8%	97.7%	63.8%	65.9%	16.2%	6.8%
R. FHL	100%	95.4%	62.5%	70%	25%	29.5%
R. TP	93.8%	93.2%	60%	52.3%	20%	15.9%
R. TA	100%	100%	75%	77.3%	21.2%	13.6%
R. PL	93.8%	93.2%	76.2%	75%	20%	18.2%
R. AbdH	98.8%	100%	63.8%	77.3%	21.2%	20.4%
L. TA	100%	100%	81.2%	79.5%	15%	15.9%
L. PL	90%	88.6%	71.2%	59.1%	27.5%	13.6
L. AbdH	96.3%	93.2%	61.2%	54.5%	16.2%	6.8%

	First Burst		Second Burst		Third Burst	
	Level Walking	Slips	Level Walking	Slips	Level Walking	Slips
R. AddT	70%	75%	40%	58.3%	10%	8.3%
R. EHB	95%	50%	65%	66.7%	10%	-
R. FHL	95%	75%	75%	58.3%	15%	8.3%
R. TP	75%	75%	55%	75%	25%	41.7%
R. TA	100%	100%	100%	75%	65%	-
R. PL	100%	100%	90%	75%	35%	25%
R. AbdH	100%	100%	65%	75%	10%	-
L. TA	100%	100%	100%	75%	35%	25%
L. PL	100%	100%	65%	58.3%	20%	33.3%
L. AbdH	95%	75%	90%	75%	-	-

Appendix E – Comparison of non-slip trials to slip trials within the muscle activity (onset, duration, and normalized magnitude) of the first burst, second burst, and third burst of the perturbed/leading limb (top) and the non-perturbed/trailing limb (bottom) in individuals with unaffected feet during contact with force plate 3 where the non-slip and slip trials occurred

(Statistical analyses was isolated to the comparison of muscle onset, duration, and normalized magnitude of the first burst during non-slip trials to the first burst during slip trials. This comparison method was followed for the second and third bursts as well)

Condition	First Burst					Second Burst					Third Burst				
	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*
	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
R. AddT															
Onset (ms)	38.0	144.2	36.0	147.8	0.485`	426.4	176.8	430.3	165.2	0.532	430.6	116.8	507.7	119.7	0.510`
Duration (ms)	179.2	74.3	180.3	59.3	0.751	182.6	89.2	188.9	70.4	0.618	209.2	90.5	181.6	51.3	0.198
Normalized Magnitude (%)	3.5	2.4	3.4	2.7	0.893	2.8	2.3	3.0	2.5	0.753	4.0	2.8	2.5	1.6	0.405`
R. EHB															
Onset (ms)	106.9	244.1	113.4	248.5	0.949	486.0	140.7	500.9	132.0	0.851`	583.1	67.3	506.3	65.2	0.293`
Duration (ms)	204.0	261.4	185.3	123.5	0.742`	174.3	57.3	194.6	62.7	0.137	178.2	63.3	139.0	62.4	0.332`
Normalized Magnitude (%)	3.6	3.7	3.8	2.1	0.196`	3.4	2.6	4.6	3.0	0.360`	3.3	2.0	4.3	4.7	0.261`
R. FHL															
Onset (ms)	13.5	121.7	19.1	102.2	0.221`	336.3	159.2	419.5	150.7	0.032*	560.9	104.6	566.8	83.6	0.781`
Duration (ms)	220.7	121.4	208.4	126.5	0.342`	180.6	69.4	179.3	66.0	0.642	161.2	48.1	160.9	45.3	0.573`
Normalized Magnitude (%)	4.8	4.0	5.0	3.2	0.328`	3.2	2.7	2.8	1.8	0.382	2.3	1.3	3.1	1.9	0.419`
R. TP															
Onset (ms)	21.4	130.8	78.4	189.3	0.012`*	380.6	167.2	392.0	190.8	0.731	567.8	114.2	498.4	88.1	0.206`
Duration (ms)	192.5	80.8	195.1	82.7	0.974	179.1	74.5	200.2	105.2	0.643	181.9	114.5	207.4	122.3	0.010`*
Normalized Magnitude (%)	4.1	4.2	3.7	3.1	0.462`	2.5	2.0	2.8	1.9	0.575`	3.7	3.8	2.1	0.8	0.261`
R. TA															
Onset (ms)	-88.4	20.6	-59.6	152.8	0.869`	452.0	182.1	450.3	186.3	0.734`	572.6	117.8	595.0	153.2	0.121`
Duration (ms)	243.9	97.4	223.3	86.4	0.083`	200.8	67.9	200.0	87.8	0.846`	171.2	51.8	147.2	35.5	0.402`
Normalized Magnitude (%)	5.6	3.1	5.0	2.8	0.005`*	3.8	2.0	4.6	2.4	0.035*	4.0	2.2	1.9	0.1	0.133`
R. PL															
Onset (ms)	-92.8	15.7	-85.2	37.4	0.184`	448.7	189.1	430.4	196.2	0.685	549.2	102.0	570.5	63.1	0.357`
Duration (ms)	291.7	117.7	251.5	81.7	0.005*	204.1	70.9	213.1	109.0	0.829`	204.1	62.4	183.5	48.1	0.177`
Normalized Magnitude (%)	6.7	3.4	6.7	4.2	0.845`	4.0	2.4	4.4	2.3	0.102	3.7	2.0	4.0	3.2	0.222`
R. AbdH															
Onset (ms)	80.4	217.9	73.2	217.2	0.995`	346.9	145.1	380.9	148.2	0.410	483.8	106.5	496.2	142.1	0.797`
Duration (ms)	217.4	124.4	233.8	145.2	0.884`	259.3	105.6	252.8	109.5	0.557	217.4	115.1	192.9	89.7	0.609`
Normalized Magnitude (%)	4.1	3.7	4.5	4.2	0.353`	4.9	2.9	5.2	3.7	0.110	2.3	1.1	4.0	3.4	0.323`

Condition	First Burst					Second Burst					Third Burst				
	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*
	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
L. TA															
Onset (ms)	46.2	76.1	63.0	112.8	0.766`	352.8	156.1	365.0	156.5	0.559`	483.3	93.4	458.7	79.0	0.543
Duration (ms)	304.8	163.3	265.6	138.6	0.302`	273.5	104.4	257.0	94.7	0.729	283.2	102.0	218.4	83.7	0.747
Normalized Magnitude (%)	6.6	4.8	6.5	4.6	0.928	6.1	2.9	6.0	2.9	0.981`	7.0	2.1	4.8	3.3	0.241`
L. PL															
Onset (ms)	-14.9	156.1	37.6	198.2	0.024`*	349.8	174.4	412.0	161.7	0.041*	460.8	88.9	515.2	85.6	0.793`
Duration (ms)	172.0	111.4	196.5	104.2	0.046`*	224.1	89.4	232.1	131.7	0.749	250.0	75.5	234.3	47.1	0.922
Normalized Magnitude (%)	3.8	1.9	4.8	2.3	0.075	3.6	1.8	4.8	3.2	0.201`	4.3	2.3	5.3	3.9	0.953`
L. AbdH															
Onset (ms)	-57.4	130.7	-11.6	190.5	0.411`	408.5	175.3	426.4	161.9	0.695	537.6	119.1	488.0	124.4	0.656`
Duration (ms)	223.8	77.1	218.7	94.7	0.888	204.3	96.1	224.0	76.2	0.309	213.5	88.3	212.3	108.4	0.221
Normalized Magnitude (%)	4.6	3.0	6.0	3.1	0.149`	3.2	2.9	4.5	3.3	0.174`	2.6	2.3	6.2	4.4	<0.0001`*

(%) Values were normalized to the peak of the EMG signal obtained during 0-100% of the stance phase, over force plate 3, for each individual participant within their level walking and slip trials for each muscle.
`ANOVA performed with a ranked transform to achieve normalcy
*Significance $p<0.05$

Appendix F – Comparison of non-slip trials to slip trials within the muscle activity (onset, duration, and normalized magnitude) of the first burst, second burst, and third burst of the perturbed/leading limb (top) and the non-perturbed/trailing limb (bottom) in individuals with Hallux Valgus during contact with force plate 3 where the non-slip and slip trials occurred

(Statistical analyses was isolated to the comparison of muscle onset, duration, and normalized magnitude of the first burst during non-slip trials to the first burst during slip trials. This comparison method was followed for the second and third bursts as well)

Condition	First Burst					Second Burst					Third Burst				
	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*
	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
R. AddT															
Onset (ms)	67.0	191.0	69.6	199.5	0.315`	341.8	171.1	426.7	119.9	0.882	-	-	-	-	-
Duration (ms)	170.4	90.0	155.9	59.2	0.608`	184.1	106.4	153.4	41.9	0.853`	-	-	-	-	-
Normalized Magnitude (%)	2.9	1.6	3.4	1.8	0.124`	1.9	1.4	3.3	1.1	0.143	-	-	-	-	-
R. EHB															
Onset (ms)	159.2	275.3	187.2	255.7	0.840	486.9	144.6	547.9	62.7	0.226`	-	-	-	-	-
Duration (ms)	148.4	55.9	150.2	39.8	0.729`	176.5	43.5	194.6	50.9	0.156	-	-	-	-	-
Normalized Magnitude (%)	3.0	1.4	2.7	2.0	0.813	3.4	1.8	2.9	1.8	0.752	-	-	-	-	-
R. FHL															
Onset (ms)	14.7	105.9	92.1	138.2	0.198	397.3	132.0	327.4	138.7	0.255	-	-	-	-	-
Duration (ms)	186.7	70.2	219.4	104.3	0.416`	171.4	51.3	311.4	191.8	0.006`*	-	-	-	-	-
Normalized Magnitude (%)	4.3	2.9	4.3	3.6	0.952	3.0	1.6	4.8	3.0	0.239	-	-	-	-	-
R. TP															
Onset (ms)	-41.1	29.1	-26.2	31.0	0.502	275.0	147.7	383.1	188.9	0.018`	485.4	145.5	560.0	17.8	0.435`
Duration (ms)	270.7	110.2	180.3	79.0	0.106`	154.2	36.5	217.1	83.9	0.185	139.2	42.1	194.8	59.4	0.307
Normalized Magnitude (%)	6.3	2.0	4.2	1.6	0.164`	3.2	1.4	4.9	2.5	0.589`	2.6	1.4	3.2	1.7	0.590`
R. TA															
Onset (ms)	-96.4	8.6	-83.8	20.0	0.083`	301.2	190.9	524.4	146.3	0.230`	-	-	-	-	-
Duration (ms)	220.8	77.3	177.7	31.2	0.095`	207.8	71.0	203.1	116.9	0.583`	-	-	-	-	-
Normalized Magnitude (%)	5.8	3.1	4.8	1.7	0.524`	4.3	2.3	6.0	3.0	0.557	-	-	-	-	-
R. PL															
Onset (ms)	-61.4	155.7	-89.8	19.0	0.712`	448.2	170.7	486.9	144.6	0.801`	579.6	69.5	607.0	57.2	0.058`
Duration (ms)	320.1	93.8	284.6	89.0	0.459	206.9	45.0	186.0	56.1	0.405	210.6	68.9	189.3	56.0	0.341
Normalized Magnitude (%)	7.8	2.8	7.5	2.1	0.736	4.6	2.4	5.6	3.2	0.697	5.0	2.5	6.8	1.5	0.404
R. AbdH															
Onset (ms)	116.9	247.6	169.4	238.0	0.317	316.5	79.9	449.0	169.8	0.404	-	-	-	-	-
Duration (ms)	216.0	105.7	314.5	229.8	0.137`	237.3	52.3	255.0	111.8	0.305	-	-	-	-	-
Normalized Magnitude (%)	3.7	3.3	6.2	4.9	0.009`*	5.0	2.9	5.2	3.8	0.545	-	-	-	-	-

Condition	First Burst					Second Burst					Third Burst				
	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*	Non-Slips		Slips		p-value*
	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
L. TA															
Onset (ms)	-3.2	82.9	39.6	71.9	0.230	247.7	172.0	369.6	184.7	0.204	-	-	-	-	-
Duration (ms)	176.5	64.4	302.9	222.4	0.131`	302.8	150.5	194.0	36.0	0.015`*	-	-	-	-	-
Normalized Magnitude (%)	3.8	2.1	6.4	5.4	0.338`	6.6	3.8	5.1	2.0	0.379`	-	-	-	-	-
L. PL															
Onset (ms)	-14.4	170.2	79.1	247.4	0.475`	363.7	209.1	306.7	220.6	0.845`	529.2	187.9	414.2	89.6	0.705`
Duration (ms)	160.4	59.1	164.3	65.5	0.356`	227.0	77.4	168.4	61.1	0.026*	172.7	34.4	372.8	89.2	0.054
Normalized Magnitude (%)	4.8	2.0	4.2	1.4	0.329	3.9	2.3	3.3	1.8	0.272	2.4	0.8	7.2	1.8	0.079
L. AbdH															
Onset (ms)	-39.4	155.7	-87.4	34.7	0.660	357.9	198.2	333.0	214.6	0.820`	-	-	-	-	-
Duration (ms)	193.0	78.1	165.2	45.8	0.012*	215.3	82.9	222.0	64.9	0.988	-	-	-	-	-
Normalized Magnitude (%)	4.6	2.1	4.7	1.8	0.252	4.4	2.3	5.5	2.0	0.498	-	-	-	-	-

(%) Values were normalized to the peak of the EMG signal obtained during 0-100% of the stance phase, over force plate 3, for each individual participant within their level walking and slip trials for each muscle.
`ANOVA performed with a ranked transform to achieve normalcy
*Significance $p<0.05$

Appendix G – Comparison of non-slip trials to slip trials kinematic variables in individuals with unaffected feet during contact with force plate 3 where the non-slip and slip trials occurred

Condition	Non-Slips		Slips		p-value*
	Mean	SD	Mean	SD	
Ankle Position (m) and Velocity (m/s)					
Ankle AP Position Maximum	1.07	0.051	0.99	0.051	<0.0001*
Ankle AP Position Minimum	0.924	0.049	0.915	0.042	0.156
Ankle AP Position Range	0.150	0.020	0.084	0.034	<0.0001`*
Ankle AP Velocity Maximum	2.99	0.367	1.71	0.407	<0.0001`*
Ankle AP Velocity Minimum	-0.010	0.040	-0.468	0.611	0.010`*
Ankle AP Velocity Range	2.99	0.369	2.17	0.650	0.0003*
Ankle Angle (˚) and Angular Velocity (˚/s)					
Ankle Angle Maximum	-16.81	6.57	-17.74	6.63	0.195`
Ankle Angle Minimum	-87.86	2.14	-86.36	3.72	0.008`*
Ankle Angle Range	71.05	5.89	68.62	6.12	0.004*
Ankle Angular Velocity Maximum	317.05	245.06	594.47	569.45	<0.0001`*
Ankle Angular Velocity Minimum	-574.91	103.99	-824.88	232.71	<0.0001`*
Ankle Angular Velocity Range	891.96	308.94	1419.35	691.52	<0.0001`*
COM Velocity (m/s)					
COM AP Velocity Maximum	3.10	8.51	3.44	9.49	0.010`*
COM AP Velocity Minimum	1.05	0.245	1.06	0.265	0.010`*
COM AP Velocity Range	2.05	8.72	2.37	9.72	<0.0001`*
COM Vertical Velocity Maximum	2.36	11.01	2.81	12.17	0.152`
COM Vertical Velocity Minimum	-0.189	0.053	-0.183	0.050	0.216
COM Vertical Velocity Range	2.54	11.01	2.99	12.16	0.143`

Positive ankle angle (+) represents plantar flexion, negative ankle angle (-) represents dorsiflexion. Anterior-Posterior (AP), Centre of Mass (COM).
`ANOVA performed with a ranked transform to achieve normalcy
*Significance p<0.05

Appendix H – Comparison of non-slip trials to slip trials kinematic variables in individuals with Hallux Valgus during contact with force plate 3 where the non-slip and slip trials occurred

Condition	Non-Slips		Slips		p-value*
	Mean	SD	Mean	SD	
Ankle Marker Position (m) and Velocity (m/s)					
Ankle AP Position Maximum	1.07	0.051	1.01	0.066	<0.0001*
Ankle AP Position Minimum	0.924	0.049	0.915	0.046	0.260
Ankle AP Position Range	0.150	0.020	0.092	0.043	<0.0001*
Ankle AP Velocity Maximum	2.99	0.367	1.75	0.441	<0.0001*
Ankle AP Velocity Minimum	-0.010	0.040	-0.434	0.597	0.018`*
Ankle AP Velocity Range	2.99	0.369	2.18	0.634	0.0002*
Ankle Angle (˚) and Angular Velocity (˚/s)					
Ankle Angle Maximum	-16.81	6.57	-17.53	6.67	0.191`
Ankle Angle Minimum	-87.86	2.14	-84.75	8.49	0.004`*
Ankle Angle Range	71.05	5.89	67.22	10.10	0.004`*
Ankle Angular Velocity Maximum	317.05	245.06	548.89	566.62	<0.0001`*
Ankle Angular Velocity Minimum	-574.91	103.99	-796.07	245.66	<0.0001`*
Ankle Angular Velocity Range	891.96	308.94	1344.96	708.03	<0.0001`*
COM Velocity (m/s)					
COM AP Velocity Maximum	3.10	8.51	3.27	9.09	0.012`*
COM AP Velocity Minimum	1.055	0.245	1.06	0.257	0.073`
COM AP Velocity Range	2.05	8.72	2.21	9.31	0.0004`*
COM Vertical Velocity Maximum	2.36	11.01	2.59	11.66	0.066`
COM Vertical Velocity Minimum	-0.189	0.053	-0.186	0.051	0.603
COM Vertical Velocity Range	2.54	11.01	2.77	11.65	0.183`

Positive ankle angle (+) represents plantar flexion, negative ankle angle (-) represents dorsiflexion. Anterior-Posterior (AP), Centre of Mass (COM).
`ANOVA performed with a ranked transform to achieve normalcy
*Significance $p<0.05$

Appendix I – Comparison of non-slip trials to slip trials ground reaction forces in individuals with unaffected feet during contact with force plate 3 where the non-slip and slip trials occurred

	Non-Slips		Slips		p-value*
	Mean	SD	Mean	SD	
AP Forces (BW)					
AP Maximum Force (1st half of contact phase)	0.13	0.06	0.13	0.05	0.798
AP Minimum Force (1st half of contact phase)	0.05	0.07	0.05	0.07	0.979
AP Force Range (1st half of contact phase)	56.52	51.74	54.97	49.24	0.578`
AP Maximum Force (2nd half of contact phase)	-0.05	0.07	-0.04	0.06	0.002`*
AP Minimum Force (2nd half of contact phase)	-0.14	0.08	-0.11	0.07	<0.0001`*
AP Force Range (2nd half of contact phase)	64.48	45.68	54.36	35.42	<0.0001`*
Vertical Forces (BW)					
Vertical Maximum Force (1st half of contact phase)	0.96	0.17	0.97	0.18	0.274
Vertical Minimum Force (1st half of contact phase)	0.66	0.34	0.67	0.35	0.093`
Vertical Force Range (1st half of contact phase)	216.14	206.55	213.25	198.85	0.818`
Vertical Maximum Force (2nd half of contact phase)	0.95	0.21	0.99	0.15	0.028`*
Vertical Minimum Force (2nd half of contact phase)	0.67	0.36	0.70	0.36	0.0003`*
Vertical Force Range (2nd half of contact phase)	199.48	163.58	203.43	221.99	0.120`
Loading Rate (BW/s)					
AP Loading Rate (After Heel Contact; 0-20%)	1.21	1.26	1.32	0.98	0.0007`*
AP Loading Rate (Prior to Toe Off; 80-100%)	1.39	1.66	1.08	1.61	<0.0001`*
Vertical Loading Rate (After Heel Contact; 0-20%)	8.09	4.04	8.63	4.12	0.008`*
Vertical Loading Rate (Prior to Toe Off; 80-100%)	-7.91	1.76	-8.62	5.70	<0.0001*

Positive Anterior-Posterior (AP) force (+) represents breaking force, negative AP force (-) represents propulsive force
All values are normalized to body weight (BW) (kg*9.81m/s^2)
`ANOVA performed with a ranked transform to achieve normalcy
*Significance $p<0.05$

Appendix J – Comparison of non-slip trials to slip trials ground reaction forces in individuals with Hallux Valgus during contact with force plate 3 where the non-slip and slip trials occurred

	Non-Slips		Slips		p-value*
	Mean	**SD**	**Mean**	**SD**	
AP Forces (BW)					
AP Maximum Force (1st half of contact phase)	0.12	0.05	0.13	0.04	0.384
AP Minimum Force (1st half of contact phase)	0.05	0.06	0.06	0.06	0.090
AP Force Range (1st half of contact phase)	49.47	49.05	47.88	44.32	0.811`
AP Maximum Force (2nd half of contact phase)	-0.05	0.07	-0.04	0.06	0.359`
AP Minimum Force (2nd half of contact phase)	-0.13	0.07	-0.12	0.07	0.197`
AP Force Range (2nd half of contact phase)	56.21	37.67	53.08	29.03	0.336`
Vertical Forces (BW)					
Vertical Maximum Force (1st half of contact phase)	0.92	0.12	0.92	0.13	0.669`
Vertical Minimum Force (1st half of contact phase)	0.66	0.34	0.66	0.34	0.981`
Vertical Force Range (1st half of contact phase)	178.05	188.35	179.48	181.36	0.558`
Vertical Maximum Force (2nd half of contact phase)	0.98	0.24	1.00	0.20	0.536`
Vertical Minimum Force (2nd half of contact phase)	0.67	0.37	0.70	0.38	0.086`
Vertical Force Range (2nd half of contact phase)	208.22	150.62	205.97	180.34	0.511`
Loading Rate (BW/s)					
AP Loading Rate (After Heel Contact; 0-20%)	1.18	0.96	1.24	1.01	0.554`
AP Loading Rate (Prior to Toe Off; 80-100%)	1.40	1.32	1.28	1.32	0.097`
Vertical Loading Rate (After Heel Contact; 0-20%)	7.81	4.76	7.99	4.90	0.958`
Vertical Loading Rate (Prior to Toe Off; 80-100%)	-8.91	1.27	-9.20	4.10	0.958`

Positive Anterior-Posterior (AP) force (+) represents breaking force, negative AP force (-) represents propulsive force
All values are normalized to body weight (BW) (kg*9.81m/s^2)
`ANOVA performed with a ranked transform to achieve normalcy
*Significance $p<0.05$

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